Alaska Department of Transportation & Public Facilities

Catastrophic Icefall Hazard Assessment, Avoidance Procedures & Mitigations Strategies - Phase II Site-Specific Studies

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The incidence of icefall is one of the most underrepresented and likely underappreciated of all the natural hazards. Falling pieces of ice are subject to melting and sublimation, and evidence of such events may be gone in a matter of days or even hours. There is very little existing research and engineering design criteria relative to icefall hazard mitigation. Alaska DOT&PF is undertaking research aimed at better understanding icefall hazards and eventually quantifying risk of impact along state highways, in an effort to mitigate icefall hazards. The research project was broken down into two (initial) distinct phases – Phase No. 1 Literature Review (completed 28 February 2016) and Phase No. 2 site-specific studies. This research report summarizes the results of Phase No. 2, and details the results of onsite studies and preliminary icefall hazard technical evaluations and risk assessments. This report also provides key icefall predictive indicators and a range of recommended mitigation solutions worthy of further consideration.

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Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4		mm	mm	millimeters	0.039	inches	in
ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
		AREA					AREA		
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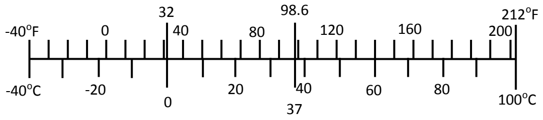
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi
These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements									

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ACKNOWLEDGEMENTS

We would like to again pay our respects to Ms. Kalia (aka "Kitty") Breskin, P.E. (deceased in 2015), formerly with the Maine Department of Transportation (Maine DOT). Kitty served Maine DOT as Senior Geotechnical Engineer for nearly 20 years, with an unwavering emphasis on public safety and a passion like no other. Kitty's willingness to tackle challenging icefall hazards in northern Maine, even in light of such limited published research on the subject, served as a catalyst for future icefall mitigation studies. Her pioneering approach, dedication to public safety, and not-so-subtle encouragement will never be forgotten.

We would like to thank Alaska DOT&PF for their willingness to formally address icefall hazard evaluation and mitigation, as they will be the first in the nation to do so. If there is any state agency in the nation with the determination to deal with this hazard, it is without a doubt Alaska DOT&PF.

We would also like to specifically acknowledge the contributions of the following individuals at Alaska DOT&PF:

- Anna Bosin, Research Engineer/Project Manager;
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ABSTRACT

The incidence of icefall is one of the most underrepresented and likely underappreciated of all the natural hazards. Falling pieces of ice are subject to melting and sublimation, and evidence of such events may be gone in a matter of days or even hours. There is very little existing research and engineering design criteria relative to icefall hazard mitigation. Alaska DOT&PF is undertaking research aimed at better understanding icefall hazards and eventually quantifying risk of impact along state highways, in an effort to mitigate icefall hazards. The research project was broken down into two (initial) distinct phases – Phase No. 1 Literature Review (completed 28 February 2016) and Phase No. 2 site-specific studies. This research report summarizes the results of Phase No. 2, and details the results of onsite studies and preliminary icefall hazard technical evaluations and risk assessments. This report also provides key icefall predictive indicators and a range of recommended mitigation solutions worthy of further consideration.

EXECUTIVE SUMMARY

Icefall hazards are not routinely considered by the civil engineering and geologic/natural hazards community. Slabs of ice have the potential to cause significant damage to persons or structures beneath the fall path; however, engineers lack the design criteria available for dealing with this “ghost-like” hazard. The 6 April 2012 icefall event near MP 113 along the Seward Highway resulted in serious injury to a motorist, and as a result, Alaska DOT&PF has undertaken research aimed at better understanding icefall hazards and quantifying risk of impact along state highways. The icefall hazard research project was initiated in 2015, and was broken down into two distinct phases – Phase No. 1 Literature Review (completed 28 February 2016) and Phase No. 2 Site-Specific Icefall Hazard Studies. This research report summarizes the results of Phase No. 2, and details the results of onsite studies and preliminary icefall hazard technical evaluations and risk assessments. It also provides key icefall predictive indicators and a range of recommended mitigation solutions worthy of further consideration.

Site studies were completed in September of 2016 (Visit No. 1) and March of 2017 (Visit No 2), in order to evaluate summer and winter conditions, respectively. We assessed seven sites total – four along the Seward Highway south of Anchorage, and three sites along the Richardson Highway north of Valdez. We documented sources of up-slope water during Site Visit No. 1 and measured observed ice slab dimensions for Site Visit No. 2. Six out of the seven sites contained well-developed ice slabs available observation. Small-scale active ice sloughing was observed at MP 113.2 along the Seward Highway due to slope heating.

Ice will generally develop when air and rock slope surface temperatures are below 32 deg. F, and when there is an upslope source of water captured by the rock slope. Solar radiation intensity, air and bedrock surface temperatures, and a consistent supply of water all affect ice slab growth rate and thickness. Steady-state surface water overflow appears to be a primary causative factor in generation of large ice slab formations. Ice will develop an adhesion strength between the rock surface and the ice slab and this adhesive bonding is the primary source of stability during subfreezing temperatures.

When the temperature of the rock slope surface exceeds 32 deg. F, melting of the adhesive interface bond commences. During periods of prolonged slope heating which act as a “triggering mechanism” towards instability, the adhesive bond may be compromised and the ice slab may be subject to failure. For slopes with angles less than approx. 4V:1H, sliding is the primary instability mechanism. For slope angles approaching near-vertical or even overhung, falling or localized slab toppling are possible failure mechanisms.

Once the ice slab has failed, icefall impacts are possible along the roadway section. “Direct impact” are those events where the falling ice mass makes initial impact. Depending of available catchment ditch width, direct impacts could fall within the ditch or could impact the roadway. Secondary effects from impact include “shatter” (break-up) and “splatter”, with icefall shatter being responsible for casting ice fragments horizontally away from the impact location. Direct impact events could impart a significant force to those surfaces being impacted, on par with that imparted from rockfall events.

Potential icefall predictive indicators include air and bedrock surface heating. In general, south facing, dark-colored high density bedrock will heat up faster than the local ambient air temperature. A study by Graveline and Germain found that an increase in cumulative melting degree days is empirically correlated with icefall occurrence, meaning that icefall is possible during prolonged periods where average daily temperatures exceed 32 deg. F. The ice mass itself is also subject to strength reductions as a function of temperature increase. Ice with coarse-grained granular structure and entrained air can indicate weakening.

Preliminary icefall impact risk assessment was completed at the seven sites, based on icefall history, traffic volume, sight distance, and slope height, and available catchment width. The MP 113 site along the Seward Highway was classified as having a “High” risk of icefall impact; MP 14 along the Richardson Highway was ranked as having “Moderate to High” impact risk; and, the MP 52 site along the Seward Highway was found to have a “Low to Moderate” level of icefall impact risk. The other four sites were ranked as “Low” icefall impact risk.

There are a range of potential solutions that could be considered for sites with elevated icefall impact risk. These include monitoring with instrumentation, upslope drainage path modification, traffic pattern modifications, slope re-grading (i.e. blasting), or adaptation of rockfall structures like barriers and netting. Ice removal is also an option; however, ice scaling is considered to be relatively risky and would likely be a “last resort”.

Based on the results of the Preliminary Icefall Impact Risk Matrix, we recommend that DOT&PF consider installation of remote monitoring instrumentation at MP 113 and MP 52 along the Seward Highway, and MP 14 along the Richardson Highway. This set-up should include a camera and weather station (like RWIS) and should also include installation of a pyranometer and slope surface (bedrock) temperature gauge. All of these would allow for observation of ice behavior with respect to changing weather conditions.

Additionally, slope excavation and/or upslope drainage diversion should be considered for MP 113. Excavation of the slope would provide for greater catchment and push the slope away from the traveled roadway. The drainage diversion would reduce the volume of water being captured by the slope crest. A traffic pattern modification consisting of a proposed two lane diversion will help to provide additional horizontal offset between the slope and the traveled lanes during periods of slope warming.

The MP 14 site along the Richardson needs a temporary (i.e. short-term) one lane traffic diversion during expected periods of slope warming, when bedrock surface temperatures are expected exceed 32 deg. F for when active ice melting is observed. Given the site’s highway width constraints, a barrier is considered to be one of the only effective long-term (low maintenance) solutions available for icefall hazard mitigation.

SECTION 1 – INTRODUCTION

Icefall hazards can be considered under-represented in its significance as a natural and geologic hazard given the lack of available information on the subject. The State of Alaska, similar to many other states, has always had ice development on slopes adjacent to public roads; however, most states have not had experience with direct impact to motorists. On the afternoon of 6 April 2012, a large icefall event occurred just south of Anchorage, Alaska whereby a motorist was seriously injured. That specific event was a catalyst, both in Alaska and nationwide, for development of preliminary criteria for mitigation of icefall hazards to the travelling public.

1.1 Problem Statement

The term “icefall” generally describes the action of falling ice particles under the influence of gravity, similar to that seen with rockfall. The term is both a verb and a noun, with the former referring to the action of falling ice and the latter referring to a thing, in this case a hazard. Icefall is a real hazard in northern tier states subject to winter conditions where ice can form and potentially fall from slopes, powerlines and structures. While icefall occurrence from towers, powerlines and structures is well-documented, falling ice emanating from slopes is not. One of the reasons for this lack of coverage in engineering and geohazards research is that ice is very much a transient hazard – its residence time is limited by temperature (i.e. air and substrate). Simply put, ice is “there one minute, then gone the next”. Based on the above, it appears likely that icefall occurrence is more common than industry research would indicate; however, it is difficult to monitor, predict and mitigate due to its transient nature.

***Figure 1** – Post-impact photo from 6 April 2012 icefall event near MP 113.2 NB along the Seward Highway. (Photo adapted for use from KTUU article pub. 6 April 2012)*

Evidence of icefall impacts to passing motorists along transportation corridors also appears relatively limited, implying that icefall impact risk to motorists is generally very low; however, for those few motorists who are impacted directly by falling ice, the results can be catastrophic. Observations within Alaska indicate that ice wasting is usually a near-vertical or crumbling event, and not typically a catastrophic outward failure. The April 2012 Seward Highway experience demonstrates icefall nearest to highways can be of greater risk than originally anticipated. In locations such as Alaska, where ice development is common and recent icefall occurrence is now documented, the Alaska Department of Transportation and Public Facilities (DOT&PF) is evaluating available hazard mitigation techniques. This is no small feat, given the lack of icefall hazard design criteria relative to both new/proposed and existing (both natural and man-made) slopes. In other words, the civil/geotechnical engineering and geologic hazards community does NOT currently plan for icefall hazard mitigation during project scoping or design. Of course, this fact makes it impractical for DOT's nation-wide to track, manage, monitor, mitigate or even plan for icefall hazards.

On the afternoon of 6 April 2012, a large slab of ice fell in the vicinity of Mile Post ("MP") 113.2 of the Seward Highway (Alaska Highway 1), severely injuring a motorist. The slab that fell was estimated to be on the order of 60 to 80 ft. in height by 20 ft. in width (Fig. 1). As a result of this direct icefall impact event, which was rare based on industry reporting of similar incidents, DOT&PF initiated state-specific icefall hazard evaluations in the winter of 2015 in order to better understand the hazard and develop initial strategies for icefall mitigation. The proposed course of work consisted of an initial literature review (Phase No. 1) to be followed by site-specific studies (Phase No. 2), both of which are further described in Section 1.2.

In undertaking these icefall hazard evaluations, the State of Alaska is being proactive with regard to development of icefall hazard mitigation strategies. This holds true even in light of the absence of industry design criteria for mitigating ice development on slopes or comparable icefall hazard mitigation planning. This study and the results contained herein represent the first-of-its-kind in North America, and it is expected that future work will build upon the preliminary framework presented within this report.

The knowledge demonstrated within this report aims to help DOT&PF staff understand the following:

- Ice development conditions that could lead to hazardous icefall;
- Meteorological/climatic controls on ice shedding events;
- Role that upslope surface and meltwater play in ice slab formation;
- Basic ice slab release and impact mechanics;
- Icefall impact risk assessment and predictive indicators;
- Importance of ice slab monitoring and maintenance;
- Types of icefall hazard mitigation solutions that may be available

1.2 Summary of Work & Intent

Scarptec was engaged by DOT&PF initially to help develop a work plan and complete Phase No. 1, Literature Review, in fall of 2015 and winter of 2016. We submitted a summary report entitled: *Catastrophic Icefall Hazard Assessment, Avoidance Procedures & Mitigations Strategies - Phase I Literature Review (1)*, dated February 2016. The report detailed the findings of our literature review and included attached tables (e.g. documented icefall events, communications with other agencies, etc.) that could be used as reference for future studies (i.e. Phase No. 2 and beyond). There are numerous references and sources of information included within the Phase No. 1 deliverable report and readers are encouraged to review this report also. The published report can be found on DOT&PF's research website: http://www.dot.state.ak.us/stwddes/research/assets/pdf/4000-158.pdf and was also submitted to the National Transportation Research Board for publication. The author was also engaged as an expert witness for the State of Alaska during legal proceedings associated with the 2012 Seward Highway icefall event, given previous icefall evaluation experience in the State of Maine.

Phase No. 2 studies were authorized in August 2016, and were initiated with field studies in September 2016 and March 2017. The intent of Phase No. 2 is to provide DOT&PF with results from preliminary site-specific icefall hazard evaluations and deliver and range of potential mitigation solutions. In short, Phase No. 2 is intended to give DOT&PF and understanding of icefall hazard risk at each site and options relative to hazard mitigation. The results of the Phase No. 2 studies also allow DOT&PF to apply some of the same conceptual framework to other sites across the state where icefall hazards could develop.

Our over-arching goals with this site-specific icefall hazards evaluation(s) were the following:

1. Enhance the safety of Alaska's travel corridors;
2. Provide DOT&PF technical and maintenance staff with the information, options, and technological tools necessary to manage and mitigate icefall hazards from within the State; and,
3. Provide DOT&PF recommendations for icefall hazard mitigation strategies;

Our authorized Scope of Work (SOW) for Phase No. 2, Preliminary Site-Specific Icefall Hazard Evaluations, specifically consists of the following tasks completed between September 2016 and 28 February 2018:

Task No. 1 – Site-Specific Studies: Will consist of on-site evaluation of slopes at the seven sites indicated below. Field evaluations would entail observation of existing slope and roadside conditions, including back-slope areas above the slope crest, presence of upslope water sources and bedrock jointing conditions for potential conduits of "free" water. We will also assess roadside ditch conditions and "effective" catchment geometry. We made a total of *two visits* over the period of this work, which consisted of the following:

- Task 1A (Visit No. 1) – Initial Site Reconnaissance Visit was in September 2016 to view slope conditions during a non-winter period. We looked at exposed bedrock substrate conditions (e.g. signs of polished bedrock, roughness geometry, and discontinuity measurements), water sources on the faces or contributing nearby, and signs of stripped or otherwise contorted/disrupted vegetation, in addition to those features noted above.

- Task 1B (Visit No. 2) – Site evaluations completed in March 2017 to assess and document ice conditions and compare conditions observed during Visit No. 1.

Our field visits were to entail assessment of existing slopes at the following seven (7) locations:

A. Seward Highway (Alaska Highway 1): MP 113.2 NB/SB; MP 74.8 SB; MP 57.8-58.4 NB; MP 52 SB;
B. Richardson Highway (Alaska Highway 4): MP 13; MP 23; MP 38.

Task No. 2 – Preliminary Icefall Hazard Assessments: This task is where data from Phase No. 1, Task No, 1 (above), and other sources (e.g. topographic maps, aerial photos) will be used to develop site-specific icefall hazard assessments at the seven locations indicated herein. This task will include comparison against historical photos available (e.g. from Phase No. 1, recent photos of only a year or two earlier), icefall analysis, kinematic (geometric) ice stability evaluations, and assessment of potential structural ice failure mechanisms, where appropriate. We will assess icefall impact risk based on potential failure mode(s), catchment ditch width, lane width, and traffic data. Upslope drainage and topographic conditions will also be studied using existing digital maps and data.

Task No. 3A – Icefall Hazard Mitigation Preliminary Solutions: Consists of development of feasibility-level icefall mitigation solutions appropriate for the seven candidate sites. Range of potential solutions could consist of recommendations relative to emergency action/management planning in cases of imminent icefall, impact zone solutions (e.g. barriers, enhanced catchment ditches, etc.), and source zone treatments (e.g. ice removal techniques, ice drapery, water diversion, topographic enhancements, or possibly even slope redesign/reconfiguration).

Task No. 3B – Site-Specific Icefall Hazard & Mitigation Option Report: Deliverable report summarizes results from Task Nos. 1 through 3. The report would detail results of icefall hazard evaluations at all seven of the subject sites and would also include potential candidate options for site-specific hazard mitigation (e.g. barriers, drapes, blasting, water redirection, slope scaling, catchment ditch reconfiguration), with consideration of short and long-term icefall mitigation solutions. The report would also include site-specific monitoring and maintenance recommendations, and preliminary mitigation cost considerations. (Note: The report is preliminary/conceptual and should not be construed as a final design document)

Task No. 4 – Development of Icefall Hazard Rating Index: Task would consider what was learned in Task Nos. 1 through 4 and incorporate results from previous Phase No. 1 studies to develop an icefall hazard rating index based on site-specific data.

Task No. 5 – Icefall Hazard Monitoring, Maintenance & Action Planning Guidebook: This task consists of the development of a field site icefall monitoring guidebook for use by DOT&PF M&O staff. This task was eliminated due to the uncertainties associated with field icefall hazard evaluation, and the findings were incorporated within this report.

SECTION 2 – FIELD STUDIES

Figure 2 *– Google Earth image capture showing location of four study sites along Seward Highway south of Anchorage.*

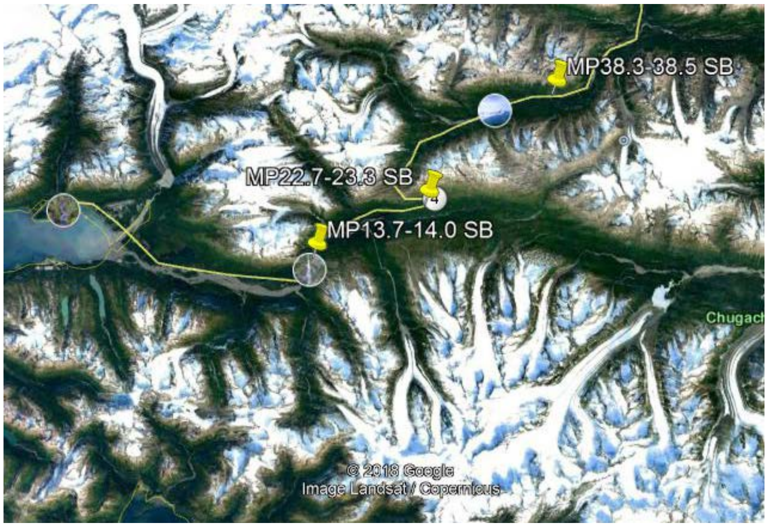

Figure 3 *– Google Earth image capture showing location of three study sites along Richardson Highway east of the port of Valdez.*

As part of Task No. 1 execution, we visited the sites on two separate occasions in order to observe slope conditions and collect data during periods of no snow pack (early fall visit) and then again during winter conditions (late winter). We collected data on roadway geometry, existing slope geometry, general rock mass conditions, ditch width, and assessed evidence for slope surface ice development. We also collected a large quantity of photographs. Information from both visits, as well as interpretations of what was observed, is summarized in the following sections below.

We completed field evaluations at the seven sites within the following intervals:

A. Seward Highway (Alaska Highway 1): MP 113.1 to 113.3 NB; MP 74.1 to 74.9 SB; MP 57.9 to 58.2 NB; MP 51.9 to 52.3 SB;

B. Richardson Highway (Alaska Highway 4): MP 13.7 to 14.0; MP 22.7 to 23.3; MP 38.3 to 38.5.

Note that the Mile Post (MP) locations indicated herein are approximate, and based on field estimates with respect to available highway mile markers. The seven site locations are indicated on Fig. Nos. 2 and 3.

2.1 Site Visit No. 1

We were onsite for Site Visit No. 1 from 12 to 18 September 2016 to collect site-specific information on existing slope and roadway conditions prior to the onset of winter conditions. Visit No. 1 focused on collection of the following, which is included as Appendix 1 (Site Visit No. 1 - Field Data Summary Sheets) attached at the end of this report:

A. Roadway Observations – Although we also referenced as-built plans for the subject sites, we collected existing roadway geometric data using a field measuring tape and laser range finder to estimate dimensions, including:
    i. Effective Roadway Width;
    ii. No. of Lanes;
    iii. Effective Shoulder Width;
    iv. Presence of Horizontal & Vertical Curves;
    v. Posted Speed Limit;
    vi. Est. Sight Distance

B. Slope Observations – Basic slope geometry and geotechnical hazard conditions, including:
    i. Effective Roadway Length (parallel to subject slope segment);
    ii. Slope Height Range;
    iii. Slope Profile;
    iv. Presence of Back-slope;
    v. Slope Material Type(s);
    vi. Slope Angle Range;
    vii. Presence & Types of Vegetation;
    viii. Slope Aspect & Dip Direction;
    ix. Presence of Internal Seepage;
    x. Presence of Surface Water Drainage;
    xi. Evidence of Slope Instability & Type(s)

C. Geotechnical Observations – Collection of basic rock mass and soil data, including the following features:
    i. Lithology;
    ii. Rock Color;
    iii. Est. Uniaxial Compressive Strength;
    iv. Weathering/Alteration Index;
    v. Texture & Fabric;
    vi. No. of Discontinuity Sets;
    vii. Discontinuity Orientations;
    viii. Est. Joint Aperture;
    ix. Evidence of Joint Seepage;
    x. Presence of Joint Infilling;
    xi. Evidence of Root Jacking;
    xii. Vegetation in Joints;
    xiii. Rock Micro & Macro Scale Surface Roughness;
    xiv. Geologic Structure;
    xv. Soil Type & Classification (USCS);
    xvi. Overburden Thickness

D. Evidence of Ice Development – Included documentation of any signs of ice development on the exposed slope surface(s):
    i. Stripped Vegetation or Soil;

   - ii. Contorted Tree Growth;
   - iii. Polished or Grooved Rock Surfaces;
   - iv. Evidence of Ice Jacking of Rock Blocks;
   - v. Site History or Ice Development or Icefall

E. Existing Rockfall Catchment Conditions – Measured features in the field using a tape measure and laser range finder, including:
   - i. Effective Ditch Width;
   - ii. Effective Ditch Height;
   - iii. Existing Ditch Condition (e.g. filled, partial, unfilled);
   - iv. Obs. Damage to Roadway;
   - v. Site History of Rockfall;
   - vi. Ditch Material (i.e. fill, swale, rock)

The data collected above was used in subsequent technical evaluation of the subject sites, which is further described in Section 9. The information was also used to develop the preliminary Icefall Hazard Rating Index and for constructability considerations during development of potential icefall mitigation options.

2.2 Site Visit No. 2

We were onsite for Visit No. 2 from 13 to 21 March 2017 in order to view the same seven sites under late winter conditions. The March 2017 site visit was ideal for the viewing of ice development, with six out of seven (86%) of the subject sites having some form of ice development (MP 13.7 - 14.0 had very little ice development at time of site visit on 15 March). This allowed us to collect data on ice dimensions and characteristics, which is summarized in Appendix 2 (Ice Slab Field Data). Specifically, where appropriate based on site-specific constraints, we collected information relative to the following:

A. Ice Dimensions – We utilized a laser range finder and tape measure to collect data on ice slab shape, thickness, width (slope-parallel) and height;
B. Ice Strength – Qualitative estimate of ice strength based on direct observations, color, evidence of fractures, and hammer impact penetration, all of which can be used to use existing correlations with compressive strength;
C. Slab Support Mode – Documented mechanisms of ice slab support, including adhesion (i.e. rock-ice contact surface), toe-support (i.e. bearing), top support (i.e. hung, cantilevered);
D. Evidence of Icefall – Documented evidence of recent icefall occurrence, including horizontal run-out (shatter) distance;
E. Location of On-Site Ice Development;
F. Presence of Running Water;
G. Ice Color – Documented color of ice
H. Ice Quality – Presence or absence of entrained fines (e.g. silt, sand, mud);
I. Available Ditch Width – Including loss of width from ice development or wind rows from snow plows;
J. Available Ditch Height – Includes height of ditch infilling snow above roadway and/or from base invert of catchment ditch.

The data collected above was used in subsequent technical evaluation of the subject sites. The information was also used to develop the preliminary Icefall Hazard Rating Index and for development of potential icefall mitigation options.

2.3 General Site Observations

Site-specific data for both visits are included as appendices to this report. In addition, site-specific technical evaluations and mitigation recommendations are detailed in Sec. 9 at the end of this report. We include a brief summary of general observations during these site visits, especially those documented during the March 2017 visit when ice development was available for viewing. The September 2016 site visit was completed in order to collect information on baseline conditions without snow and ice cover. Such observations are unique to each site and were used as a basis for preliminary technical evaluations and subsequent recommendations relative to concept-level mitigation options.

As one might expect for Alaska in March, weather consisted of winter conditions. Snow and ice were observed in most ditches and locally obscured portions of the slope face at the seven sites. Weather was generally cold and windy, with daytime temperatures in the high teens (Richardson Highway) through low thirties (Seward Highway) and lows in the single digits (Richardson) through high teens (Seward). Significant daytime heating was witnessed on 20 to 21 March 2017, especially at MP 113 area which coincided with ice melting and observed ice wasting due to high solar radiation, as further described in Sec. 9.

While in the field, we used a Trupulse© laser range finder and tape measure to measure distances in the field. We also used an azimuthal Brunton© Compass to record slope angles, trends and information on discontinuity attitude. A geologic hammer was used to estimate ice and rock strength.

Note that this report references mile post (MP) numbers which are approximate, based on actual mile markers in the field and use of a laser range finder. In most cases we could shoot distances directly off these mile markers (MP numbers shown herein should not be misconstrued with "Milepoints" which are shown in Table 1 below). The number of specific sites and site limits were chosen during initial project scoping and actual limits of slopes investigated may also include segments of the same slopes directly adjacent to those indicated by MP numbers alone. In other words, if ice (or conditions that could lead to ice) were observed on the same slope segment intended by those MP's shown in the scoping phase, we included those findings within this study.

TABLE 1
Approx. Milepoint Conversions

Highway	Mile Post (MP)	Milepoint
Seward	113.1 – 113.3	112.1 - 112.3
	74.1 – 74.9	73.1 - 74.1
	57.9 – 58.2	57.3 - 57.6
	51.9 – 52.3	51.4 - 51.8
Richardson	38.3 – 38.5	42.6 - 42.8
	22.7 – 23.3	26.4 - 27.0
	13.7 – 14.0	17.7 - 18.0

SECTION 3 – ICE SLAB DEVELOPMENT CONDITIONS

Ice development on slopes has been documented to cause short and long-term degradational effects on rock slopes, including effects like ice jacking, surcharging, accelerated weathering, ice-jammed discontinuities (which impedes drainage and allows destabilizing water pressures to increase), and increased frequency of rockfall and icefall (*2*).

It is important to summarize the likely conditions that support ice development on slopes. Ice will generally develop when two criteria are initially met:

1. The presence of "free" available liquid water; and,
2. Temperatures fall below the freezing point (32 deg. F/0 deg. C).

Figure 4 *– Stable ice slab feature near MP 74.8 SB on Seward Highway (Photo by Scarptec, Inc.)*

Significant water discharge velocities and high winds will tend to impede ice development on slopes; however, both of these are relatively short-lived phenomena with respect to the duration of winter conditions. As the ice is subject to freezing, it will develop an adhesive interface strength that allows it to bond to the slope surface. The ice slab will grow outward and downward (vertically) and will generally mimic the flow path of the water seepage along the slope face (Fig. 4). Lateral ice cascade growth parallel to the slope face will occur significantly slower than the outward thickening and downward components of growth, resulting in smaller "icicle" or larger "slab" type formations.

Once bonded to the slope, the mass of ice will be supported either in suspension (e.g. localized free-hanging growth like an icicle), by interface "bonding" along the slope face (e.g. frozen waterfall feature) and to a lesser extent by direct bearing on the substrate. Ice slab stability is primarily derived from this interface bond strength, which when removed, results in slab displacement.

The importance of an abundant water supply and consistent freezing temperatures on ice development and required support conditions are described in additional detail below.

3.1 Sources of Water for Ice Slab Generation

The relative abundance of water at a site is critical to whether ice will form and more importantly, to the possible size of the ice formation. Simply stated, if the volume of readily available water is minimized, then there will be a corresponding reduction in ice slab volume (Note: Refer to Sec. 8 on mitigation options for more details on surface water management options).

Steady-state surface water overflow appears to be the primary causative factor in generation of large ice slab formations. Well-developed slabs of ice will be formed from the freezing of consistently flowing upslope water as it is intercepted or "captured" by the slope crest. Direct impact by precipitation (e.g.

snow, rain) falling on the actual slope face does not appear to be a major source for significant ice development. Furthermore, presence of fracture-controlled seepage is less significant in the development of ice than direct overflow of upslope surface water. Although joint-controlled seepage will add to total available water supply, it does not appear that fracture flow alone will supply the necessary volume of water needed to generate large ice slabs. Addition of water, either from existing up-gradient perennial streams or downslope migration of meltwater from snowpack, will provide the consistent discharge needed to generate significant ice growth.

The preceding statements are based on Phase No. 2 of the icefall hazard studies, which found the following at the study sites:

- surface water discharge locations observed in September of 2016 were in close proximity to major ice features observed in March of 2017;
- Trickling water was heard behind (or within) major ice slabs observed in March 2017;
- Ice formation morphology (vertical columns or spires fused together) suggests steady-state sources of water available for consistent cascading, freezing and outward growth of ice crystals;
- Re-freezing of upslope water generated from snow melt appeared to be a major causative factor in the addition of surface water to the slope system;
- Ice was found to have a blue hue at four of the seven sites (57%), which includes eight of the 17 (47%) specific ice slab features witnessed in March 2017. The blue hue indicates relatively thick ice growth as light is diffracted through the ice medium, and thickness is an indication of consistent addition of water.

Important Note: Water migration pathways like perennial streams or annual meltwater gullies are subject to change and meander over time, resulting in changes to discharge points over the slope face. Snow accumulation and subsequent metamorphosis will result in diversion (or even temporary damming) of water drainage pathways above the slope, so ice slab formation location is subject to change from year-to-year. This may present a challenge to the predictability of ice development location, which requires icefall hazard evaluations to focus on intervals, not just a specific point on the slope.

3.2 Temperature Controls on Ice Development

Temperature plays a very important role in both the formation and mass wasting of ice slabs. The temperature of the rock slope surface (i.e. “substrate”) and the air both become important at the onset of initial freezing. The air temperature must be at or below 32 deg. F (0 deg. C) in order for fresh water ice to develop, assuming that the water seepage is at a relatively low discharge velocity; however, the slope surface may initially be just above freezing at very small distances into the rock. Once ice forms on the outer surface of the slope and penetrates the surface asperities, the mere presence of ice will help to further reduce the slope surface temperatures along the ice-rock interface, as bedrock will take longer to cool than the surrounding air.

In order for significant ice slab development to occur, temperatures must be consistently cold enough to allow ice to grow but not so cold that all available water sources are completely frozen. As described further below, there is an optimal range of conditions for ice slab growth to occur. The initial freezing period must be followed by prolonged periods of cold weather to generate continual ice growth. During periods where the average daily temperature falls below the freezing point, ice can be expected to develop. The longer the duration of below freezing average daily temperatures, the higher the likelihood that ice growth will be maintained and not be subject to melting or mass wasting. Depending on location with the State of Alaska, under most normal circumstances the onset of highway ice development would be expected to occur between October and November of any given year.

Incoming direct solar radiation intensity is high enough to induce partial melting of snow pack and subsequent slope overflow. As observed during site-specific studies, snow melt can still occur on days when the ambient air temperature is at or even 4 to 6 deg. F below freezing.

Solar Radiation Intensity

Incoming solar radiation will warm the air mass and bedrock, and initiate melting of the snow pack when sun intensity is high. In this regard, slope aspect also plays an important role in ice development (and ice wasting as will be described in subsequent sections). In general, south facing slopes will be subject to increased durations of sunlight which increases the likelihood of snow pack melting on backslopes above the ice-forming rock slopes.

The term “albedo” (α) is used as an indication of reflectivity of incident electromagnetic light with values ranging from 0 (black body absorption) to 1 (perfectly ideal reflector). A black surface like asphaltic pavement has a very low albedo ($\alpha < 0.1$-0.2), while snow has a very high albedo value ($\alpha \sim 0.9$). Although snow is an excellent insulator and has a higher albedo than bedrock or even ice ($\alpha \sim 0.5$-0.7), some melting will still occur. This melting will produce water that is ultimately captured by local topographic lows – in this case, the roadway limits. Along the drainage path, the water may be captured by the slope crest which will “feed” subsequent ice growth at and near points of interception. Surfaces that absorb more incident energy (e.g. bedrock) will tend to warm faster than those that are good reflectors (e.g. snow).

Air Temperature

The air will be heated by incoming solar radiation. Ice will consistently develop and be retained on the slope during prolonged periods where the average daily temperature is less than 32 deg. F (0 deg. C). Ideal conditions for ice development are during periods of consistent daytime seepage from upslope water sources, followed by late day and night time re-freezing. Periods where the daily temperature never rises above the freezing point will limit upslope melting and downslope migration of water, both of which “feed” the ice and allow for subsequent growth. Conversely, periods of excessive warmth will virtually eliminate the possibility of freezing due to elevated surface temperatures and rapid water flow velocities. Another way of looking at temperature control on ice slab development is through the concept of “degree days”, which is further described in Sec. 4.2.

Bedrock Surface Temperatures

Bedrock surface temperatures play an important role in initial ice bonding (and melting). The very outer surface of the rock needs to be at or below freezing temperatures (32 deg. F) for initial crystallization of ice. The bedrock may be significantly warmer only a matter of inches into the surface. The initial ice crystallization acts as a “seeder” for subsequent adhesion and build-up of additional ice. High density bedrock surfaces with a higher proportion of dark minerals (or staining) will have lower albedos and will heat-up faster than light colored rocks. For example, under the similar conditions, basalt would heat faster than a typical granite due to the high content of dark-colored minerals. Conversely, the onset of initial freezing is likely also delayed on surfaces with low albedos; however, this is short-lived under prolonged winter conditions. Bedrock surface heating also plays a critical role in de-bonding as presented in Sec. 4.

3.3 Initial Bonding

The ice will develop an "adhesion" bond strength between the substrate rock slope surface and the ice mass itself. This is important because in the opposite sense, once the slope surface warms sufficiently, the ice slab surface contact area will be reduced due to melting. Reductions in bonded surface area are directly translated into a net loss in the minimum adhesive contract strength required to support the weight of the ice structure. Adhesion is strength along a surface developed between two *dissimilar* materials. For example, the bond between concrete and steel or concrete and rock would be an adhesive type bond. Similarly, the surface area along an ice to bedrock contact is an adhesive bond, characterized by its adhesive strength. Adhesive interface strength is presented in greater detail in Sec. 4.3.

Large-scale slope "roughness" also aids in the development of ice growth. Irregularly-shaped slopes or those with benches provide additional surface area available for bonding. Vegetation can be considered a type of roughness perpendicular to the slope, which will assist in ice retention, especially with woody growth like saplings and small trees.

3.4 Slab Support Mechanisms

Ice slabs may be locally, partially or temporarily supported on the slope over the residence period. For example, well-developed ice sheeting on near vertical slope faces could be supported at the toe by direct bearing on rock. In similar fashion, a mid-slope bench from previous blasting activities could serve as a local ice slab bearing feature. Ice slab stability is unlikely to be compromised during extended periods of below freezing average daily temperatures due to contact adhesive strengths; however, slab loads will be distributed to contact points as the bond adhesion is lost due to melting.

Figure 5 *– Partial ice column direct bearing near MP 113.2 NB on the Seward Highway (Photo by Scarptec, Inc.)*

Depending of slope angle and profile shape, ice structures may also garner a portion of their overall stability from external structural support mechanisms, including the following:

- Direct bearing – Slab bears on or against a bedrock (or soil) surface where a portion of the weight is transferred to the medium below as shown in Fig. 5;
- Top-support – Ice is held up in part due to presence of a near horizontal slab on a bench or slope crest feature;
- Frictional Interlocking – The "waviness" from asperities on the slope face will contribute to localized support as the slab grows outward.

In general, direct bearing and top support conditions would be most likely on steep slopes. The total contribution to overall slab stability consists of the adhesion, frictional and structural support components; however, adhesion remains the single most important factor in overall stability during below freezing conditions, as only a fraction of the load is supported by the other three components which become mobilized once adhesion bonding is minimized.

SECTION 4 – MECHANICS OF ICE SLAB RELEASE

4.1 Introduction & Technical Approach

As noted in Sec. 1.1, “icefall” is a general term that describes the falling action of ice particles under the influence of gravity, and a term that also describes ice shedding events as a type of natural hazard known as “mass wasting”. Much like the closely related geologic hazard known as “rockfall”, we venture to develop an understanding of the process that initiates icefall at the time of incipient failure. Ice slabs will fall due to the application of a “triggering mechanism” and by a failure process that is quantifiable, even if initially only by estimation. If we can quantify the precursors, site conditions, and ice build-up geometry that may lead to icefall generation (the “hazard”), then we can develop strategies and solutions that aim to minimize the chances of icefall impacts on the travelling public (the “risk”). The remainder of this section provides an overview of ice slab failure processes and formed the basis for the site-specific technical analyses described in Sec. 9.

4.2 Icefall Triggering Mechanisms

By definition, an initial triggering mechanism will induce failure to commence in a slope system with the potential for instability. The system could be stable or even meta-stable until the onset of this trigger at the moment of incipient failure. For example, heavy rainfall could be considered a triggering mechanism for the translational failure of a shallow landslide. Ground vibrations, like those imparted by earthquakes, can be a trigger for rockfall or landslides. Falling ice hazards are also subject to triggering mechanisms, and understanding what these triggers are and how they develop will help shed light on the timing and frequency of the hazard. At any given site, conditions may already exist for instability, including unfavorable geology, steep slopes, and presence of water, to name a few; however, it is the triggering mechanism that frequently gets these icefall events to “go”.

Although there may always be more than one trigger, ***the primary icefall triggering mechanism is a net positive fluctuation in ambient air and rock surface temperature (slope warming)***. Short duration changes in temperature can occur in the winter; however, the likelihood of longer duration warming periods typically occurs in the late winter and early spring. Increases in temperature will affect icefall occurrence and will apply to the air, slope surface (i.e. “substrate”) and to the ice mass itself. Heating of the fluid air mass occurs from convective heat transfer (“convection”) and heating of the solid rock slope surface and ice mass will occur via convection and solar radiation (from direct sunlight).

Just as the relative humidity of the air mass will impact the rate of ambient air temperature change, the density (which implicitly accounts for bulk rock lithology, grain minerology, and porosity) and color of bedrock will affect the rate of heating. Simply put, darker colored and dense bedrock exposures will generally heat up faster than light colored or low density earth materials. Ice and air have lower specific heat capacities than granite, meaning that the bedrock takes less heat energy input to raise the temperature by 1 deg. C., as there is an inverse relationship between specific heat capacity and material density. Again, this is relevant because increases in air and rock surface temperature – particularly, rapid increases in temperature are expected to increase the incidence of ice shedding events.

As further described in Sec. 7 on icefall “predictive indicators”, thermodynamic constraints on the incidence of ice shedding events in alpine environments have been studied by a few researchers, who have found that ***an increase in cumulative degree days (DD) above freezing is correlated with icefall occurrence*** (*3*). A Degree Day (DD) is simply the net difference between average daily temperature and some reference temperature threshold (e.g. 0 deg. C and March 1st for the cited study). This implies that consistent, extended periods of warming could be a trigger for icefall.

The initial and primary triggering mechanism for ice slab release will be increases in both ambient air and bedrock surface temperatures, unless there are less frequent events like seismic shaking, severe winds, corollary impacts from falling debris above, or other contributory trigger events which add to the probability of release.

4.3 Ice-Rock Interface Strength

Ice-rock contact interface strength is primarily correlated to the adhesive and cohesive strength of the ice along this boundary, as has been studied by researchers (*4,5*). There are numerous studies cited in the literature regarding ice adhesion (and cohesion) to steel frames for aerodynamic engineering applications and also for chemical engineering research relative to minimizing adhesion to certain surfaces. There is literature on glaciology and mechanics of large ice flows; however, there is limited literature on ice slab stability on rock slope substrates. As a result of this fact, we need to develop simple criteria that are appropriate for preliminary icefall analyses. Much of the technical approach described herein is based on our direct observations in the field, our experience with rock slope stability and rockfall analyses, and based partly on relationships (and values) described by researchers.

Based on our interpretation of previous documented icefall events and our observations in the field, it is apparent that ***most icefall events originating from rock slopes will ultimately fail from a loss of interface adhesive strength at the moment of incipient failure***. Ice slab failures generally occur on slope surfaces dipping toward the highway, and upon application of increased temperatures, are subject to undermining and loss of support. The loss of support can be from down below where the slab was bearing on solid ground, or it can be from loss of adhesive area along the contact surface (from melting) – either way, the slab is subject to shear forces directed along the ice-rock failure plane. This is not to exclude tensile failures which could occur during rotation (i.e. toppling) of the slab, or crushing of the slab toe due to loss of compressive strength. Given the extensive slope-parallel contact area that ice will have in comparison to other cross-sectional orientations, it's the contact shear strength that plays the greatest role in the stability of large ice slabs on highway rock slopes. In light of this finding, we go on below to describe the ice-rock interface shear strength contribution (or lack thereof) to the stability of ice slabs at the onset of failure.

Cohesive & Adhesive Strength

Ice-rock contact strength is primarily characterized by the adhesive and cohesive strength of ice along the interface. Attributes of the host bedrock joint surface strength become minimized as the triggering mechanism of temperature increase controls heating of the bedrock and air, which induces changes to internal ice strength and ice-rock contact strength. Ice slab interface strength is reduced to the strength of the ice adhesive bond and the ice's own internal cohesive strength component. The adhesive bond of ice may be greater than the cohesive strength in cases of significant surface area. The cohesive strength component on the other hand, may result in nearly linear failure ("decohesion") primarily through the ice. The loss of adhesion ("delamination" or "debonding") would typically happen first, as the contact area of the adhesions is reduced through increases in temperature and subsequent melting from heating of the host rock and air mass as shown in Fig. 6. ***Ice failure through delamination does not typically leave much ice on the slope face, whereas decohesion failures will leave small pieces of ice remaining (adhered) to***

the face. This is significant because most failures (and post-failure photos) reviewed by us indicated very little remaining ice on the face, pointing toward delamination failures through loss of adhesive strength.

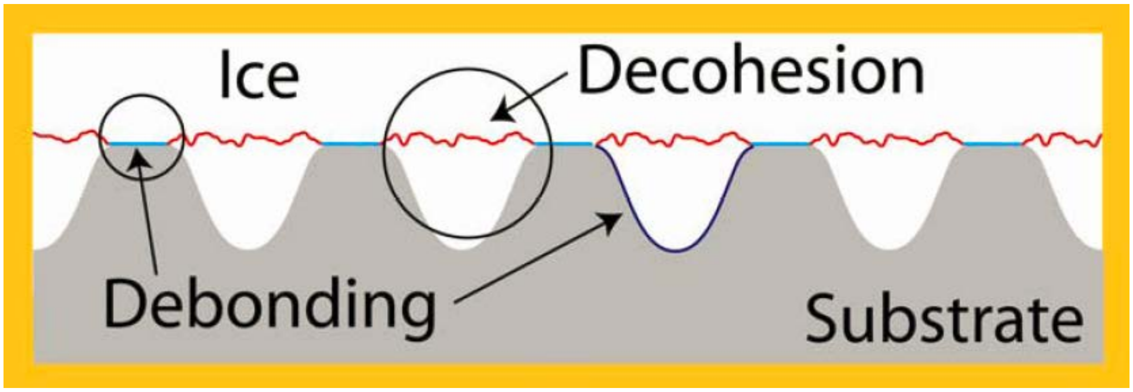

Figure 6 – Idealized graphic of cohesion vs. adhesion loss along an ice-rock interface
Image adapted from Fortin & Perron (*6*)

“Adhesive” strength (or simply “adhesion”) is strength along a plane developed between two dissimilar materials. For example, the bond between concrete and steel would be an adhesive type bond. Similarly, the surface area along an ice to bedrock contact is an adhesive bond, characterized by its adhesive strength. Based on published research for aircraft development, adhesion values of ice to various metal surface types can range between 10 and 300 psi (0.07 to 2 MPa) in the ice temperature range of 23 deg. F (-5 deg. C) to -4 deg. F. (-20 deg. C), respectively (*6*). Alternatively, research for aggregates used in pavement design shown an adhesive bond strength (under tension loads) of 15 to 36 psi (0.1 to 0.25 MPa) (Note: The studies cited this range were for ice adhesion to various surfaces including metal and gravel size pieces of granite and gabbro. It is expected that these adhesion values would be low for most rough bedrock surfaces; however, this range permits comparison with the cohesion values cited below)

“Cohesive” strength (or “cohesion”) refers to the strength of a contact surface between two materials of like quality, and is frequently used to characterize a materials internal strength and resistance to shear deformation. For example, certain soils like clay have an intrinsic cohesion value which develops from chemical bonds (e.g. hydrogen bonds) and may be measured in the lab. Intact bedrock for example, has a relatively high cohesive strength. Based on published research (*7*), cohesion values of fresh water ice can vary between 783 psi (5.4 MPa) and 1,363 psi (9.4 MPa) at ice temperatures between 32 deg. F (0 deg. C) and 3 deg. F (-16 deg. C), respectively. (Note: The cohesion ranges shown above were developed for studies of a freshwater ice sheet and assumed a confining stress was present, which is not representative of the icefall case. As such, it’s our opinion that the shown range of cohesion would be on the high-end for use in icefall studies; however, the ranges at the lower end are close to those shown for adhesion values. Intent is to show the order of magnitude that is a reasonable range to use for analyses)

Both cohesive and adhesive strengths can come to significance when estimating the strength of an ice-rock contact surface as shown in Fig. 7. When tensile forces are applied to the ice-rock surface at very low temperatures, cohesive strength may dictate surface strength (*6*). When shear forces are applied along the ice-rock boundary, both adhesion and cohesion will apply; however, the distribution of each will depend on the “roughness” of the contact surface area and the amplitude of the bedrock waviness or “asperities”.

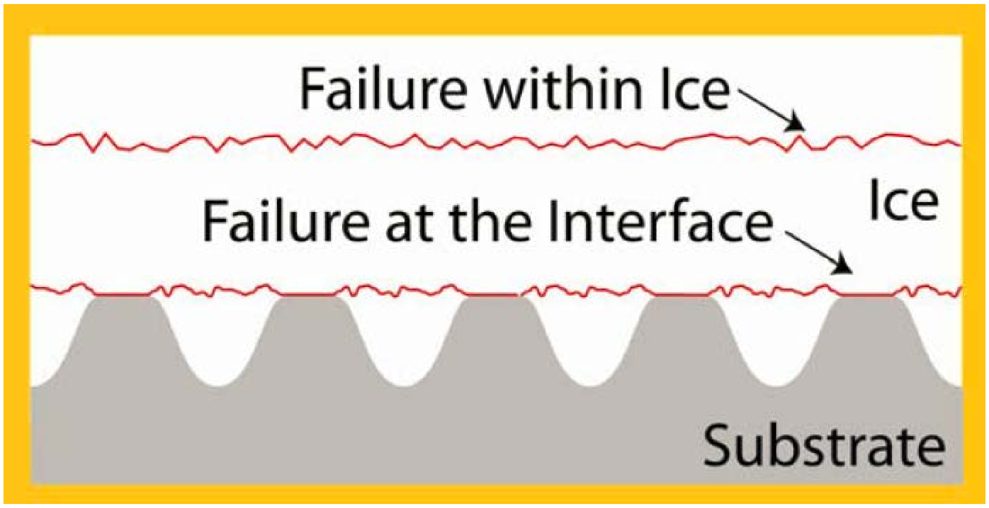

Figure 7 – Idealized graphic of potential failure surface along an ice-rock interface
Image adapted from Fortin & Perron (*6*)

Published literature (*6,8*) indicates that ***at temperatures close to the freezing point, adhesion bonding will dictate tensile and shear interface strength. Loss of surface area due to melting effectively reduces the minimum bond strength needed for ice slab stability.***

Frictional Strength

The frictional component of the interface shear strength is comprised of two components, the first being, base friction (small scale) afforded by grain roughness, with sandpaper being a good analog. The second component is the large-scale roughness afforded by undulations in the slope surface. Natural or mechanical breaks, discontinuities and weathered surfaces all add to the large scale ("macro-scale") roughness, all of which would typically be visible from some distance away. Ice will tend to develop and prefer on slopes with significant large-scale roughness profiles, including on benches created by rock excavation and blasting activities.

Frictional strength is dependent on the friction force applied on a surface and the coefficient of friction for that same surface. In this instance, the coefficient of static friction (μ_s) applies, which is equivalent to the shear force required to induce motion divided by the normal force applied across the sliding surface. The coefficient of static (not kinetic) friction of ice contacts is highly dependent upon the roughness profile of the "other" material over which it slides, as shown in the following section.

Frictional values for materials of the same type and quality (e.g. rock on rock) are frequently cited in literature and can also be tested in the lab using a direct shear box. The situation is not as simple when there are different materials on both sides of the contact surface, which is the case with ice on rock. Different materials require development of a "composite" friction angle that considers properties of both materials.

Given the likely ice creep rate during melting along the ice-rock interface, base friction is expected to be overcome and will be very low. Furthermore, studies of ice-rock contact frictional strength alone appear to indicate significant spread in strength estimates; however, larger-scale roughness along the slope will increase shear strength due to dilation (overriding) of the slab over asperities during sliding. The contact surface of the sliding plane will break-down as sliding progresses. Macro-scale roughness may also result in the development of localized shear resistance pockets which can then be overcome in periods of rapid temperature change, resulting in a torrent of cascading ice material.

The base friction angle of fresh water ice has been shown by researchers to be temperature dependent and vary between 2 deg. at 32 deg. F (0 deg. C) to as much as 14 deg. at -40 deg. F (-40 deg. C) (*7*). The warmer temperatures and onset of melting associated with icefall would indicate that a very low base friction angle would apply, if used at all.

Interface Strength

Ice will conform to the topography of the rock slope surface as water from above refreezes and builds-outward. The frozen water will penetrate asperities and adhere to the roughness profile along the slope face, resulting in a composite shear strength. This interface shear strength is made up of contributions along (or through) rock surface asperities, ice infilling within such asperities, and ice internal (cohesive) strength within and above the asperities.

As described in the two previous sections, there are two general components that go into development of contact shear strength, those being, a bond (cohesion and/or adhesion) strength and a frictional component due to displacement and dilation along a specific plane. Under most normal circumstances, both of these components can be quantified and added together to estimate shear strength along a surface. There are numerous shear strength criteria utilized within research and industry, but one of the most widely used is the Mohr-Coulomb Criteria (MCC) that for specific materials and contact surfaces provides for a relationship between applied shear stress and normal stress. The MCC can be shown by the equation:

$$\tau = \frac{V}{A} = (C + A) + \sigma_N \tan \emptyset_b \qquad \text{(Eq. 1)}$$

Where τ is interface shear strength; V is the shear load force along the interface, C is cohesive strength; A is adhesive strength; σ_n is the normal stress applied perpendicular to the surface; and $\emptyset_b$ is the basic angle of internal friction ("base friction angle") along the surface (micro-scale roughness). Base friction angles can be estimated in the field, derived from tables in literature, or tested in the laboratory on relatively smooth "saw-cut" surfaces. The $\tan \emptyset_b$ term is equivalent to the coefficient of static friction (μ_s) noted above.

The frictional component (second term in Eq. 1) can be expanded to include macro-scale roughness from bedrock surface "waviness" (from asperities) in addition to the micro-scale roughness. The frictional resistance contribution from larger-amplitude surface asperities can be included as an additional angle ("i") above that of the base friction angle (*9*). Based on this, Eq. 1 can be re-written as:

$$\tau = (C + A) + [\sigma_N \tan(\emptyset_b + i)] \qquad \text{(Eq. 2)}$$

To put all of the above in simple terms, the shear strength along a composite (hybridized) ice-rock contact surface is the additive contribution from both ice bond strength and the frictional resistance parallel to the interface. Published fresh water ice intact shear strength values vary between 29 psi (0.2 MPa) and 580 psi (4 MPa) depending on temperature, loading rate, ice type and grain size (*7*). Saeki (*8*) shows ice to concrete ("coarse" surfaced) adhesion shear strengths of 73 to 109 psi (0.5 to 0.75 MPa) at 32 deg. F (0 deg. C). There is a marked reduction in ice shear strength as specimen temperature increases.

It can be seen from Eqs. 1 and 2 that the frictional component is dependent on the magnitude of the applied normal stress on the surface. So the larger the normal stress (or force), the larger the total frictional component. Normal forces developed from ice slabs along highway slopes, although considerable, will be generally less than would be seen along rock-rock (joint) surfaces. This is true because the density (unit weight of 57.2 pcf) of ice is typically only 30 to 40% of the density of most bedrock. In addition, ice slabs developed on rock slopes are surficial features and do not have additional static surcharges applied. Ice slab thicknesses at the moment of failure also will be minimized after some period of initial melting. (Note: Exceptions to the preceding statements would be under glacial ice loading situations or with floating arctic sea ice slabs; however, for most civil or mining engineering rock slopes, relatively low normal forces are expected are expected with ice slab failures)

Ice shear strength may also be locally increased due to "artificial roughness" on the slope, for example, in the case of vegetation (including trees), as the ice clings to additional surface area on the slope. The opposite may be the case with soil or loose snow covered surfaces, as melting along an ice-soil contact would result in marked reductions in interface shear strength; however, solid slabs sliding on soft compliant surfaces will frequently result in a "plowing" effect, which would partially impede further displacement.

We note that cohesion, adhesion and friction angle of ice is strongly correlated with changes in temperature and applied strain rate (*7*). Increasing ice temperature results in a net reduction of ice strength (tensile, shear and compressive), including adhesive shear strength and internal ice cohesive strength. Given the relatively low pressures applied at the ice-rock boundary, it can be assumed that any minor changes in strain rate can be considered constant.

If we assume based on our field observations that icefall typically occurs during periods of warming, as noted above, then we can make a few simplifying assumptions about the shear strength of ice-rock contacts. Firstly, the values for base friction angle are expected to be very small at temperatures close to 32 deg. F (0 deg. C) (*4*) such that we can neglect them. Secondly, delamination failures are most frequently observed in the icefall reviewed events, indicating a loss of adhesive shear strength (A_v). With these simplifications, Eq. 2 then becomes:

$$\tau = A_v + \sigma_N \tan i \qquad \text{(Eq. 3)}$$

Equation No. 3 is used to complete sensitivity analyses for ice slab shedding (sliding) events through loss of interface shear strength in subsequent sections. In the true physical sense, there will be small contributions from base friction angle and ice cohesion, but removing these two parameters from consideration allows us to simplify and be conservative (lower shear strength) at the same time. We believe that this approach is appropriate for this preliminary level of technical evaluation. Specific values selected for use in subsequent site-specific analyses are present in Sec. 9.

Interface adhesive tensile strength (A_t) is derived from lab tests described in the literature, and can be used to develop ice-rock bond tensile strength (32 deg. F/ 0 deg. C) irrespective of normal force or slope roughness. These value would be used to evaluate falling or rotating ice slabs.

Tensile, Compressive & Bending Strength

Much like ice shear strength, “intact” (not interface) ice compressive and tensile strength is inversely proportional to temperature, so as temperature increases, strength decreases. Based on published values in the literature, ice compressive strength at 14 deg. F (-10 deg. C) typically varies between 1,100 and 1,500 psi (8 to 10 MPa) (*10*). At 0 deg. C ice is between 150 and 300 psi crushing strength. For example, compressive strength estimates would be appropriate to use for evaluations of ice resistance to internal crushing. Ice compressive strength (σ_c in Pa) as a function of grain size (d at cm) and temperature (T) can be estimated according to the following empirical formula (SI Units):

$$\sigma_c = 9.4 \text{ x } 10^5 (d^{-\frac{1}{2}} + 3|T|^{0.78}) \qquad \text{(Eq. 4)}$$

Ice tensile strength can be estimated as 10 to 15% of ice compressive strength and various authors show typical ranges between 145 and 319 psi (1 and 2.2 MPa) at 19 deg. F (-7 deg. C) (*10*). Unlike compressive strength, temperature has very little influence on ice tensile strength (*10*). Tensile strength would come into play when slabs are subject to toppling (rotation) on very steep or reverse-sloped surfaces as they pull away and fall from the contact surface. The flexural (bending) strength of ice typically varies between 70 and 170 psi (0.5 to 1.2 MPa) (*10*) and would be appropriate for use when evaluation buckling of tall, slender ice slabs.

4.4 Ice Failure Mechanisms

The process of ice slab wasting on highway rock slopes is complex and degenerative, and is first characterized by loss of adhesive ice-rock contact shear strength, followed by periods of subsequent slab deformation as the structure tries to support its own self-weight. Ice mechanical strength is temperature dependent; however, in order for icefall to take place, general warming in the late winter or spring months is the typical case that would induce failures. Ice mass deformation can result in further deterioration of contact strength as the slab undergoes deformation along the existing rock slope. Depending on slab geometry, fall height and presence of intact ice bridges, ice slab failure will initiate primarily by direct shear failure, and would then be followed by additional slab deformation during fall. Ice may break up into a series of smaller blocks during fall or upon impact, and may also be subject to extensive fall or impact generated crushing.

In similar fashion to rock, potential failure mechanics of ice slabs may consist of the following instability modes shown below. Note that this does not imply that these failure modes have taken place or are likely, rather, that these modes are possible failure scenarios and include:

1. Slab Sliding at Source Zone (Source Zone initiation) – Failure commences from loss of shear strength along the ice-rock contact, as described above. Heating of bedrock substrate will speed up the rate of melting along contact even if air temperatures are close to freezing, and reduce adhesive bond shear strength along this interface. ***For slope less than approx. 4V:1H (76 deg.), loss of interface shear strength and subsequent slab sliding appears to be the most likely failure scenario.*** In cases where ice is supported along the slab toe (i.e. base either at ditch or at bench level), this support may degenerate due to toe settlement and crushing due to reduction in ice strength during periods of warming.

   A slab of ice failing by shear can be modeled as an equivalent block of weak rock sliding along an ice-rock contact surface, according to Eq. 3 from the preceding section. Once failure commences, frictional resistance helps to reduce ice slab velocity and energy; however, it can conservatively be assumed that micro-scale frictional contributions to shear strength along the rock-ice contact are effectively nil as they are likely very low and at the critical case, are reduced to the macro-scale roughness of the slope (i.e. wavelength of asperities).

2. Slab Toe Crushing (Internal Bearing Capacity Failure within Ice) – In cases where slab geometry is such that stresses result in crushing of the ice section, ice slab failure may result. This would be the case when the ice slab cross-sectional area is minimized from melting, resulting in concentrated stresses along the point(s) of contact. This could take place within either the source zone or impact zone. If the toe is supported on rock, frozen material or ditch ice, then the toe may stay intact; however, then global slab toe failure is less likely because this means that conditions are likely still cold enough to support ice adhesive strength. Ice crush strength can be estimated via Eq. 4 and compared to estimates of critical cross-sectional slab area based on field measurements. Ice that has been melting and subsequently weakened may take on the appearance and consistency of "punk" ice. For rock slopes along highways, global failure is considered an infrequent mode of failure. (Note: in cases of complex or "mixed-mode" failures localized ice crushing (i.e. compressive) strength may be exceeded, for example, when sliding commences along the upper portion of a slab while the lower portion remains intact; however, this would be a subset of sliding failure)

3. Slab Toe Failure in Weak Material (External Bearing Capacity Failure) – This failure mode would consist of loss of bearing support in soils, weak rock, or frozen ground underlying the ice slab. The slab would either "punch" through the soil and/or start sliding within the weaker substrate material. This mode of failure is expected to be very infrequent.

4. Slab Toppling (Source Zone) – This type of rotational failure can occur if the slope face (or outside ice face angle) is between vertical and battered backwards into the slope (i.e. "overhung") such that the slab center of gravity falls outside the slab limits. As with shear failure case noted above, the ice-bedrock contact must be partially debonded in tension in order for the slab to release. Evaluations of this failure mode would rely on adhesion bond tension strength and/or cohesive bond tensile strength. Toppling ice slabs are expected to be limited in overall thickness as ice strength is likely compromised at the onset of failure, resulting in crushing action as the ice rotates and falls. Likewise, the slab rotation arm length is expected to be reduced by the non-rigid nature of the ice as it rotates outward. In other words, low ice strength will reduce the horizontal extent of slab impact (the same could not be said for a rigid slab of rock, for example, which could rotate large distances before breaking-up). Large-scale topples would transition to pure block falls at relatively small distances away from the slope. In addition, most cut slopes are designed at an

Figure 8 *– Direct icefall impact & shatter at MP 13.9 Richardson Highway. Slab partially rotated outward during fall from overhung slope on 13 December 2017. Photo courtesy of AKDOT&PF.*

angle less than vertical (and certainly not designed as overhung), which would reduce the likelihood for commencement of toppling.

A subset of structural slab toppling case described above is that of the localized case, where a portion of the slope is "overhung" and a remaining slab of ice of finite size is adhered to the slope. Instead of a tabular sheet structure, the ice is an amorphous or blocky shape subject to a component of rotation prior to or during free-fall. An example of localized block rotation and fall is shown in Fig. 8. ***Much like the shear interface failure described in detail above, this localized toppling is a likely failure scenario along very steep and especially "over-hung" slopes.***

5. Slab Buckling (Source Zone) – Can occur in cases where the slab structural rigidity is low due to reduced cross-sectional area (i.e. from melting) and excessive slab heights. Reductions in ice strength due to melting, crushing and fracturing could also result in eventual buckling type failures. Much like other failures cases cited above, slab debonding must be present in order to allow for slab movement away from or down along the slope face. Ice strength is likely compromised at the onset of failure, resulting in crushing action as the ice is subject to deformation. Large-scale "intact" buckling type failures are not expected to be frequent along highway rock slopes; however, localized cases of "dynamic" slab buckling could occur as portions of larger slabs let loose on flat slopes and impact (or ride over) stable ice down below.

6. Falling Ice Blocks & Catchment (Impact Zone) – Considers the blocks after they have been released and in cases where adhesion tension strength is compromised (e.g. free-hanging slab with only top support). This would include ice blocks subject to free-fall or those originating from source zones above the slope crest (rolling down from above). ***For near vertical slopes, slab "fall" is a likely ice slab failure mechanism.***

In reality, the actual failure mode is likely "complex" and is not necessarily as simple as just one mechanism. It is more likely that a combination of successive events results in the eventual failure of an ice slab. In addition, for large slabs there may be a series of failures before the entire slab is wasted. For example, a portion of the slab may fail by toppling initially, leaving other portions of the slab unsupported. The remaining portions of the slab could then fail by loss of shear strength and subsequent sliding.

The critical factor that ties all of the preceding scenarios together is that loss of ice-rock interface strength is required for initial displacement of the ice slab at the onset of failure. If strength of the ice-rock contact is not compromised, the release mechanisms that lead to global ice failure will not be initiated.

SECTION 5 – ICEFALL IMPACT HAZARDS

As shown in previous sections, icefall will occur after loss of the minimum required interface adhesive strength required to support the slab's own weight. After the initial release, falling ice slabs will start to break-up either from "first impact" (direct strike on slope or other hard surface) or from internal slab deformation (e.g. rotating, crushing). The impacts discussed within this section are those within the "impact zone", which is the zone where falling ice blocks make contact with objects along their fall path <u>after</u> initial release and displacement.

As further described by Scarpato & Woodard (*2*), there are three icefall hazards that result after the ice slab failure and which are presented below, those being:

- Direct impact (primary);
- Impact shatter (secondary);
- Impact splatter (secondary)

5.1 Direct Impact

Direct icefall impact hazards have the potential to be catastrophic depending on the location of initial impact. Direct impacts result from actual point-to-point contact with pavement, pipelines, utilities, or vehicles. Direct impact hazards for icefall can be similar to those for rockfall with respect to kinetic energy and collision damage. The 6 April 2012 icefall event near MP 113.2 NB along the Seward Highway was a direct impact event (Fig. 1). Another example of an icefall direct impact event is shown in Fig. 9, where a slab of falling ice impacted a tour bus outside of Terrace, British Columbia. Direct impact to the roadway was also observed more recently at approx. MP 13.9 SB along the Richardson Highway, although no vehicles were struck.

Figure 9 *– Direct icefall impact damage to bus near Terrace, British Columbia, courtesy of Terrace Daily Online, February 5, 2011.*

Large free-falling slabs of ice originating from near vertical slopes could produce upwards of 1,000 to 1,500 kilojoules (kJ) of kinetic energy and impact forces between 175 and 225 kilo-pounds (kips), as was demonstrated from back-analysis of the 2012 Seward Highway event. Large-scale slab failures of this magnitude could result in significant structural damage and even fatalities, however localized or infrequent such major events may be. Smaller direct impact events are capable of breaking glass, light poles and bending roadway signage.

Ice slabs subject to sliding along shallower slope angles are slowed by frictional resistance and slab break-up along the sliding surface, both of which will reduce block velocity and resulting impact forces.

5.2 Impact Shatter

Figure 10 *– Impact shatter from a spring icefall event in Gilead, Maine. Photo adapted courtesy of Haley & Aldrich, Inc.*

Impact shatter results when an ice particle breaks-up upon initial contact with a substrate, like pavement, walls, rock outcrops, or a roadside ditch. Similar to "flyrock", an unintended consequence from rock blasting, smaller ice projectiles can be liberated even if direct impact is within a dedicated rockfall area, as shown in Fig. 10. Such projectiles could enter, for example, a roadway and cause a hazard to the traveling public. Shatter could also induce driver over-correction as motorists swerve to avoid impact with an ice fragment. Historic shatter event entry into the roadway was noted at three of the seven Phase No. 2 study sites.

5.3 Impact Splatter

Figure 11 *– Impact splatter from icefall impact in Gilead, Maine. Note mud and gravel in road. Photo adapted courtesy of Haley & Aldrich, Inc.*

Impact splatter results from initial ice block contact, where the substrate material yields and is sent travelling away from the point of impact. An example of this could entail an ice block impact in a wet, soil-filled rockfall ditch, where soil, water, and small fragments of rock are cast horizontally, resulting in debris entering the roadway as shown in Fig. 11. Splatter could be considered a subset of shatter and although seemingly rather benign, could rarely result in minor vehicular impacts or driver overcorrection. Splatter debris entry may also require increased maintenance demands along the roadway shoulder.

5.4 Icefall Impact Mechanics

Ice block impacts are expected to have little (if any) structural impact to flat roadway surfaces given that the kinetic fall energy is used to facilitate crushing during fall and upon impact; however, above grade structures such as lighting, signs, and vehicular traffic are very much susceptible to icefall impact and subsequent damage. Once ice slabs have released by loss of adhesive strength along the ice-rock contact, there are four primary ways to evaluate ice block fall:

1. Post-Failure Inspection: Involves evaluation of icefall event after it happens, which would include collection of field data like estimated pre-failure slab dimensions, post-failure block sizes, lateral limits and height of debris field, ice grain fabric and texture and photographs. This information can be used to estimate block impact energies, fragmentation, and failure limits.
2. Use of Rockfall Modeling: Rockfall models can be used as an analog for icefall on a case-by-case basis where the blocks will be falling along a slope impacting the surface, as was successfully shown in the State of Maine in 2011 (*2*). This would be appropriate where ice blocks of finite size were falling from source areas above the slope crest, over slopes with benches or on slopes with lower slope angles. The use of rockfall models as an icefall analog loses value as slopes become very steep, overhung or where large slabs fall under the influence of gravity only (free-fall) with little slope impact. Challenges with the use of rockfall models include accounting for the break-up and loss of mass as the ice block impacts the slope as ice behaves as a weak rock and is subject to comminution upon impact. Consideration need to be given to potential winter conditions like snowfall or ice in ditch and impact that plow wind rows may have on effective catchment geometry. Additionally, accounting for coefficients of normal and tangential restitution and slope surface roughness under winter conditions (e.g. snow, ice, wet soil) is challenging. Falling ice is also expected to have a larger sliding component and a very low contact friction angle which complicates reliability; however, in the right slope geometry, rockfall models may be a good “first-pass” for cases where discrete ice blocks are subject to bouncing and rolling from source zones above the slope crest. Irrespective of model use, catchment ditch geometry needs to consider block fall size, block strength, impact surface, fall path and distance to roadway.
3. Use of Kinematic Equations: When used with some simplifying assumptions, “first principles” physics and kinematic equations can be very helpful with estimating impact mechanics, including fall time, kinetic energy, impact force, and block fall velocity. The author has successfully used this approach for design of rockfall barriers and canopies on steep and overhung slopes where limited block impact is expected to occur during free-fall, and which compares well with results from rockfall models.
4. Numerical Models: Although their use is beyond the scope of this preliminary study, icefall deformation mechanics can be modeled using numerical models. This would include modeling of initial failure through the period of run-out and arrest of mass movement, allowing the modeler to estimate the block(s) travel distance.

SECTION 6 – PRELIMINARY IMPACT RISK ASSESSMENT

A hazard is a “thing” or an “event”, whereas risk quantifies the chances that such a hazard will impact an asset of value (e.g. humans or infrastructure). The mere presence of a hazard such as icefall does not necessarily mean that there is a risk of impact. For example, if an icefall hazard exists at a site with very wide and deep catchment ditches, then the corresponding impact risk to the general public may be very low. In an effort to help define the potential significance of the icefall impact risk, we developed a preliminary icefall impact risk matrix based on our studies of seven highway sites with documented ice development across south-central Alaska. The remainder of this section briefly describes what we found and concludes with a general qualitative icefall impact risk table, which could be used by DOT&PF M&O staff to help understand site-specific controls on impact risk from future icefall events.

6.1 Ice Recurrence Interval

Although year-round presence of water and routine ice development alone are not reliable indicators of icefall impact risk, continual ice presence on a nearly year-in-year-out basis must be given due consideration. Climate controls and presence of water could be included as separate entries; however, this is implicitly incorporated within this heading, as melting of snowpack (which is hard to predict) can be a major contributor to water source.

6.2 Icefall History

Includes relative weight of documented icefall history and frequency, including “type” of icefall impact hazard inclusive of direct impacts to roadway, shatter or splatter.

6.3 Traffic Volume

The quantity of vehicles passing a given point along the highway is an important metric relative to the probability of impact risk. In general, the higher the frequency of vehicles passing a specific point, the higher the likelihood of impact. Given that icefall frequency has historically been most active during the late winter and early to mid-spring months, consideration would normally be given to use of monthly average daily traffic (MADT) during the March and April; however, average annual daily traffic (AADT). AADT values are higher than MADT which makes the risk evaluation more conservative to account for climate change impacts, site variability, icefall evaluation uncertainties and expected long-term increases in traffic usage. We also note that the 13 December 2017 icefall event near MP 13.9 along the Richardson Highway occurred in a “non-typical” time of the year so too much emphasis of traffic data from March and April may be less than ideal. Traffic data can be derived from DOT&PF Region-specific Annual Traffic Volume Report documents.

6.4 Sight Distance

There are two types of icefall impacts in the general sense, those being instances where the ice impacts a structure (like a car) and the other being where the structure impacts the ice. The latter case becomes applicable when icefall has already entered the roadway at which point it is struck. Alternatively, if one motorist is impacts the ice block in the road and the next motorist has obstructed vision, then there could be an accident between motorists – with the root cause being ice fragments residing within the roadway. In this context, sight distance is important for minimizing corollary impacts to ice (or other debris) within the roadway. Measured or estimated sight distances are accounted for within the risk matrix.

6.5 Slope Height – Catchment Geometry Ratio

This is defined by the catchment ditch width and depth. In the context used herein, width is used to define the minimum horizontal icefall catchment distance observed at a site. Catchment may already be available relative to rockfall hazards at any given slope location along the highway; however, it should be noted that rockfall catchment ditch design does not explicitly account for icefall. In general, the more width available for catchment, the lower the probability that ice slab direct impact (or shatter) will enter the roadway. It should be noted that the modifier "effective" should be used when referring to catchment, as unmaintained ditches with significant accumulations of debris could reduce desired (design) retention capacity.

The ratio of slope height (H) to available catchment width (w) is an important metric for two reasons:

- Defines the horizontal offset between the roadway and the slope; and,
- Quantifies the slope height with respect to available catchment width for icefall (and rockfall) capture.

There needs to be some threshold with which to measure ditch width adequacy. Rockfall models using industry-available software (e.g. CRSP, RocFall) can be used as a "first-pass" for ice blocks subject to rolling or bouncing on flatter slopes; however, for block free-fall, rockfall models are less useful especially for "weak" material subject to plastic yielding or break-up. In order to help define this threshold for minimum catchment adequacy, it is suggested that catchment be a minimum of 25% of the slope height, or in ratio form:

$$\frac{H}{w} < 4.0 \qquad \text{Eq. 2}$$

Although somewhat outdated with respect to its use today, this ratio was initially shown by rockfall pioneer Authur Ritchie in his landmark 1963 paper on rockfall ditch design criteria (*11*). This paper provides a design chart for falling, bouncing and rolling rocks, based on field tests of rockfall retention capacity. In most of the site-specific cases observed in Alaska, it was observed that ice block near free-fall from steep slopes was the dominant and that bouncing or rolling was minimal. Ritchie's design chart maintains an approximate required minimum ditch width to slope height ratio of nearly 1 to 4. This ratio is useful as a general indicator of existing catchment width adequacy with respect to direct impact.

However, most conventionally available rockfall models, design charts and criteria do NOT account for break-up upon impact (only some advanced numerical models can handle this), as shatter is not traditionally considered as part of the catchment evaluation process. Icefall shatter can be a significant hazard to those using the roadway, given that ice will typically be in a weakened state (like weathered shale or siltstone) when it make first impact. Secondary shatter hazards are difficult to quantify, as failure type and impact energy will dictate the "throw" distance and whether the ice "flies" or rolls. Based on empirical evidence from the documented icefall events in Alaska, it appears that ice can be cast outwards to distances approaching the slope height (30 to 55 ft.) or 2 to 9 times the direct impact distance, which in many cases crosses both lanes of the highway. Given that shatter trajectory prediction is such a challenge, the risk matrix only uses direct impact distances as the basis for minimum available catchment adequacy and assumes that shatter will be handled by field maintenance controls such as barriers or as otherwise presented in Sec. No. 9.

6.6 Icefall Impact Risk Matrix

Based on the criteria outlined above, we prepared a matrix for site-specific evaluation of direct icefall impact risks presented on the basis of “High”, “Moderate” or “Low”. This Preliminary Icefall Impact Risk Matrix (PIIRM) is included as Appendix No. 4, and was used in a site-specific context for assessment of risk both with and without mitigation, as further detailed in Sec. 9. It should be noted that the PIIRM is a preliminary, qualitative measure of relative icefall impact risk at each site. An analog for this approach is the Preliminary Rating associated with the Rockfall Hazard Rating System (RHRS), developed by the Oregon DOT and FHWA (*12*) for assessment of rockfall hazards along highway slopes. The Preliminary Ranking used in the RHRS is used as a basis for differentiating between slopes with low, moderate or high potentials for rockfall. Slopes ranked as “low” would be monitored but likely not mitigated. Conversely, slope ranked as “high” would have an elevated possibility of rockfall and consideration of mitigation efforts would likely be warranted. Mitigated risk after application of potential solutions is shown in Table 8.

SECTION 7 – KEY ICEFALL PREDICTIVE INDICATORS

There are some key indicators that will serve as precursors for ice slab release. Understanding and monitoring the slope for observations of such indicators will help M&O field staff plan and make necessary arrangements for potentially imminent icefall hazards. The following section focuses on predictive indicators and thresholds that could be used prior to the incidence of icefall (not for ice development), as measured by key observations made remotely or in the field. Refer to Sec. 7 for additional details on recommended monitoring equipment and frequency.

7.1 Air Temperature Trends

Researchers in Quebec, Canada presented a general empirical correlation between periods of consistent warming and the frequency of icefall incidence. Their study found that an increase in cumulative melting degree days (DD) was correlated with icefall occurrence (*3*).

Using Eq. 5 below, a Degree Day (DD) is simply the net difference between average daily temperature and some reference temperature threshold (0 deg. C and March 1st for the cited study), and the DD would be calculated as:

$$DD = \left\lfloor \frac{(T_{min}+T_{max})}{2} \right\rfloor - T_{ref} \qquad \text{(Eq. 5)}$$

Where: T_{min} and T_{max} are minimum and maximum daily temperatures, respectively; T_{ref} is the reference temperature; and DD is cooling Degree Day.

For example, if the reference temperature was 0 deg. C, and the daily minimum and maximum temperatures were 2 deg. C and 12 deg. C, respectively, then the DD value would be 7 deg. C. In similar fashion, cumulative degree days would be summation of all positive DD values obtained after a threshold date.

Graveline & Germain (*3*) cite case studies in northern Quebec, Canada based on 30 ice block fall events recorded by the Quebec Ministry of Transportation (QMT) between 1987 and 2011. The results show a rapid increase (53.3%) in icefall occurrence during the first positive 35 to 100 DD (deg. C) measured, indicating that increased probability of icefall occurrence may be correlated with periods where there is a sustained duration of above average daily temperatures. In Quebec, this initial intense phase of icefall occurrence tended to coincide with the middle of April through early May. After this period, the relative frequency of icefall events reduced to 23.3% in Phase 2 (early to mid-May) and 23.3% in Phase 3 mid-May through early June). The authors hold that **cumulative DD measurements are a "*good indicator of ice block fall hazards*"** but that much work remains relative to understanding of collapse mechanics.

As shown in Appendix 3, we used the above approach to compare observed temperature conditions for the 6 April 2012 icefall event at MP 113.2 on the Seward Highway and the 13 December 2017 event at MP 13.9 on the Richardson Highway. We used weather data from the McHugh Creek and Keystone Canyon RWIS locations, both of which are approx. 1.5 mi. south of the respective highway slope locations.

Based on the data from McHugh Creek and Keystone Canyon RWIS sites, we found that the icefall appears to have been initiated after 17 and 11 days of consistent average temperatures above freezing, respectively. Up to the dates of both icefall events, there was an estimated 75.5 melting DD (Deg. F) for MP 113 site and 51 melting DD (deg. F) for MP 14 area along the Richardson Highway. Although the approach using degree days is purely based on empirical evidence, it provides insight into the temperature ranges where icefall could be triggered. This is not a measurement of direct incident solar radiation, but increases in temperature are can be coincident with increases in sunlight duration and intensity.

There appears to be a general empirical correlation between the number of cumulative days of heating represented by MDD values and the frequency of icefall at both sites. Duration of above average daily temperatures (and day time highs) above freezing was clearly enough to induce icefalls at both sites. Site-specific monitoring (e.g. RWIS type set-up) could be implemented to both observe and record icefall trigger temperatures. (Note: this approach using DD is still experimental and needs additional evaluation)

7.2 Bedrock Surface Temperature

The previously cited researchers found a general correlation between the onset of seasonal periods of consistent climate warming and icefall frequency; however, the significance of bedrock surface temperatures cannot be overstated. Bedrock temperatures will have a higher significance than air temperatures, as the rock heats up quickly and melts the ice-rock contact. It is reasonable to assume that the referenced study above implicitly includes the contribution from incoming solar radiation warming; however, we provide some additional context for this very important triggering mechanism below. Monitoring of bedrock temperature either remotely or by field visits could be implemented when ice-supporting bedrock surface temperatures exceed 32 deg. F (which may even be when air temperatures are still below freezing).

Bedrock Color

Bedrock surface temperatures will heat up relatively quickly in contrast with adjacent snow and ice due to their intrinsic albedo value, which is primarily based on mineral assemblages within the bedrock crystal fabric. The color of the bedrock and any surface staining will affect the rate of heating. The addition of moisture around the perimeter of the ice slab (e.g.) from slab melting) will aid in "darkening" the rock and will aid in the further lowering of the rock's albedo, as shown in Fig. 12. In turn, this effect will result in an increase in the rate of rock surface heating. Moistened bedrock surfaces even were found exuding steam on one such day in March of 2017.

Figure 12 *– Ice slab melting on dark colored rock near MP 113.2 NB on the Seward Highway (Photo by Scarptec, Inc.)*

Intact Rock Density

In addition, bedrock density is important to how the surface conducts heat across the slope face. Exposed rock slope surfaces with high intact rock densities will heat-up faster than ice, snow or soil. Dense rocks will also be more efficient conductors of heat energy. Rock density and color can both be correlated with lithology (rock type and mineralogy), which means that rocks like basalt and gabbro will generally heat-up faster than limestone due to abundance of ferromagnesian minerals.

Slope Aspect

The direction that the slope faces (i.e. “aspect”) will have an impact on the duration of sunlight received by the rock surface. In general, southerly-facing slopes will be subject to increased durations of intense sunlight which means that south-facing slopes could heat-up faster than slope faces with other orientations.

7.3 Ice Color

The color of ice can be an important indicator with respect to ice strength, as documented by glacial research. Ice with a clear and or blue hue (Fig. 13) is generally compact, free from air voids and micro-crystalline, all of which is correlated with higher strength. Conversely, white or gray (Fig. 12 and right side of Fig. 13) ice is considered relatively weak due to the presence of entrained air bubbles (porosity) and coarse crystal structure. Color can be used as a proxy for ice strength compressive (crushing) strength, which is temperature dependent. This is important because internal ice weakness can lead to fracturing and separation between individual slabs, which could lead to icefall. At temperatures close to the melting point, ice has a limiting value of crushing strength of approx. 150 to 300 psi.

Figure 13 *– Strong blue ice slab with adjacent weak white ice near MP 38.3 SB on Richardson Highway (Photo by Scarptec, Inc.)*

“Dirty” brown ice is frozen water that has been contaminated with sand, silt and/or clay. Coarse rigid soil inclusions like sand or gravel would be expected to increase ice internal resistance to crushing; however, the effect of ice contamination on adhesive bond values is unknown.

7.4 Ice Texture

Ice with coarse-grained, randomly-oriented crystals and contains entrained air bubbles is generally significantly weaker than ice with micro-crystalline textures and no visible signs of porosity. A photographic example of weak ice texture is included as Fig. 14. Fallen ice fragments can be inspected for color and texture to make qualitative estimations of ice slab internal strength. White or gray granular textures indicate weak ice, which may indicate candidacy for eventual break-up and subsequent fall from the main ice slab.

Figure 14 *– Sample of fallen coarse-grained weak white ice from ditch at MP 113.2 NB on the Seward Highway (Photo by Scarptec, Inc.)*

7.5 Icefall History

Sites with a documented icefall history will have a higher probability of future icefall given that conditions for icefall have existed at the site before. Icefall impact frequency should be recorded and reviewed, both in the catchment ditch and for those events which actually enter the roadway. Sites with a documented history of ice development automatically have a higher probability of icefall occurrence; however, ice development alone does not necessarily infer that impact risk is elevated. Site-specific icefall history is not a physical precursor to slab release but it is important to weighing which sites could present icefall impacts.

7.6 Active Melting & Seepage

Evidence of ice slab melting and associated water drainage are indicators of both a warming rock slope and melting ice slab, as shown on Figs. 12 and 15. The presence of consistently moist or dripping areas around the perimeter of the ice block demonstrates active “debonding” from the slope and may indicate an increased likelihood for near-term active slab wasting.

7.7 Interface Displacement

As described in detail throughout this report, the integrity of the ice-rock contact is of paramount importance to the stability of the ice slab. If the interface shows signs of displacement, this could be a precursor for icefall. Displacement could consist of the following:

Figure 15 – *Interface retraction seen at MP 113.2 NB on the Seward Highway in March 2017 (Photo by Scarptec, Inc.)*

- *Interface Retraction* – Ice slab pulls away from the bedrock surface due to combination of adhesion loss from melting (debonding) and resulting internal deformation as the slab tries to maintain static equilibrium on the slope. Signs of retraction include the appearance of small to medium size lenticular voids between the ice and the rock wall (Fig. 15);
- *Translation* – Active slab movement down slope due to loss of adhesion-controlled shear strength. This type of movement would indicate that failure is imminent (or has already occurred) as the slab is relying on very limited and temporary frictional contributions to shear strength. In this condition, the slab is basically “hanging” temporarily on macro-scale slope roughness features. Evidence of translation movements includes presence of voids along the interface, active small-scale sloughing and signs of slab positional changes;
- *Dilation* – Is a subset of translation where the slab “rides over” the top of asperities on the slope surface, showing evidence of lenticular voids between the ice and the bedrock. The contact surface essentially opens-up for a portion of the slab length.

Ice slab dimensions (including thickness) can be quickly estimated use a laser range finder, photographs and a field notebook. Evidence of slab movement or wasting can be compared to the previous day’s photos and measurement notes.

7.8 Internal Deformation

Observations of accelerating internal slab deformation can also be precursors to icefall. Ice will weaken during melting and may locally detach from the face due to loss of adhesion. The combined effect could lead to break-up and fissuring within the overall slab. Signs of this will include the development of fractures and possible sloughing as the slab re-equilibrates on the slope. Comparative photographs and simple observations in the field can be used to look for signs of internal deformation.

7.9 Summary

In general, increases in air and rock surface temperature can result in the following effects:

- Changes in ice strength and behavior - increases in ice temperature up to and above the point of freezing (32 deg. F/0 deg. C) will result in a significant corresponding reduction in ice strength (compressive, tensile, and shear). Ice rheological properties can also change from more brittle behavior to that which is more ductile.
- Icefall occurrence may be triggered during periods of consistent local climate warming between 50 and 75 DD’s. This data could be used to track site specific DD’s to-date during the spring, and then estimated based on short- to intermediate range weather forecasts; however, this approach is based requires additional research and analysis.

- Av. bedrock surface temperatures greater than 32 deg. F.
- Heating of the rock mass – increases in bedrock substrate temperature will reduce the interface strength along the ice-rock contact surface.
- Icefall events will tend to occur more frequently in afternoon hours as the slope gets the full benefit of incoming solar radiation. This does not exclude the possibility of icefall events in the morning hours, but suggests that there is a higher probability of occurrence in the afternoon hours.
- As adjacent ice wastes away, there is more surface area of bedrock exposed for heating. Bedrock heats up faster than air from direct incident sunlight (solar radiation) resulting in differential heating of the rock surface and ice mass.
- Edges of exposed ice slabs will tend to pull away and detach from the slope face prior to the ice center as the surrounding heat from the bedrock is transmitted (via conduction) to the ice. Prior to major releases, small pieces of ice will tend to be shed around the edges of the main slab.

Most of the predictive criteria indicated in this section can be gathered both in the field (and remotely) and from short to medium-range weather forecasts for a specific area.

SECTION 8 – ICEFALL HAZARD MITIGATION SOLUTIONS

There are a wide range of mitigation options available for the rockfall and landslide hazards communities, ranging from hardened structural systems to hazard removal to long-term slope monitoring. Many of the same tools and methods can be used to mitigate icefall hazards; however, developing an understanding of where such hazards may develop and the severity of the hazard condition are both critical during allocation of resources. The icefall hazard shares many similarities with other types of slope hazards but there are some stark differences that will impact selection of mitigation solutions, the most obvious of which are:

- Estimation of icefall hazard interval (i.e. limits of possible icefall along highway);
- Recurrence interval and frequency of significant ice development on the slopes;
- Icefall impact risk to those using the highway;

There are numerous methods of icefall hazard mitigation that may be employed at any given site, dependent on the level of impact risk to those using the highway. It is assumed that these solutions could be applied to both existing and proposed slopes; however, ***access to the slope crest could be a site-specific issue based on right-of-way (ROW) restrictions which should be confirmed prior to selection of mitigation alternatives***. As part of Task No. 3, we have provided a brief summary of the range of potential options before we describe location-specific icefall hazard mitigation recommendations, as there may be other icefall hazard locations that develop across the State of Alaska. Note that there are a range of other options that could be considered but we only present the solutions that are reasonable based on the industry state of knowledge and technology. The options described herein may not be appropriate for all sites, but may be ideal for others. The intent of the listing shown below is to highlight a wide range of potential solutions. Some may be employed directly by DOT&PF, while others may require input from geotechnical or natural hazards mitigation consultants. Preliminary site-specific specific recommendations by area are included in Sec. 9.

8.1 Monitoring Methods

Monitoring methods make use of human intelligence, basic field observation and measurements and where appropriate, use of instrumentation to document field conditions over some period of time. ***The key component to any reliable monitoring program is a monitoring plan***. In the absence of such a plan, key findings and coordination efforts may be diminished and inefficient. In general, methods of monitoring can consist of the following:

1. <u>Visual Monitoring & Inspection</u> – Includes measurement and documentation of pre- and post-ice field conditions (e.g. slope and catchment), ice dimensions, ice development limits, and icefall frequency record. Site visits could be documented via notes in field tablets/notebooks, photographs or short videos. High-strength steel bars could be installed during summer months and used as measuring staffs to help estimate ice thickness. The results of site monitoring could be included within a GIS-based hazards database, rock slope inventory, or eventually within an overall Geotechnical Asset Management (GAM) Program much like Alaska's Unstable Slope Management Program (USMP). In addition, icefall event could be recorded within DOT&PF's Maintenance Management System (MMS) for tracking of event frequency and allocation of resources.

   With a well thought-out overall plan, pre-populated field forms and a reliable M&O field guide, ***visual monitoring and inspection is a relatively cost-effective way monitor ice hazards***. This is especially true in the short-term, where DOT&PF is trying to understand the full extent of potential icefall hazards state-wide adjacent to public travelways.

2. Instrumentation – Use of instrumentation can be a powerful way to monitor ice development and mass wasting over time. Types of instrumentation could include the use of:
   A. Radar – synthetic aperture radar to monitor real-time movements of ice slabs with remote telemetry system;
   B. Periodic ground-based LiDAR (light detection and ranging) scans;
   C. Deployment of onsite remotely operated cameras and/or video monitors (Fig. 16) much like DOT&PF's Road Weather Information System (RWIS);
   D. Installation of automated site-specific remote read-out weather stations (RWIS);
   E. Install of on-slope instrumentation such as a pyranometer which measures solar irradiance on a planar surface and it is designed to measure the solar radiation flux density (W/m2); and thermometers on/in the rock slope surface to monitor temperature;
   F. Use of reflectorless total stations (survey equipment) to measure ice dimensions

Figure 16 *– RWIS onsite instrumentation for remote data transmission (Photo by Alaska DOT&PF)*

8.2 Drainage Modifications

Drainage modifications are expected to be highly effective given that significant ice slabs will not develop without the presence of upslope surface water. This assumes that DOT&PF has right-of-way access to modify the terrain. In cases where such access is not permissible, then use of a "slope easement" may be required. This form of mitigation would include the following site enhancements or alterations:

1. Regrade Back-slope Areas – Grade existing (or proposed) back-slope topography such that upslope surface water is channeled away (or parallel to) the slope face, and discharged at a designated location. This could include the use of drainage swales, underdrains or wide channels depending on required hydraulic capacity (requires evaluation of upslope drainage area, runoff coefficients, etc.). Alternatively, if local site topography permits, pitch slope surfaces away from the slope crest and transmit water to a settling pond/velocity dispersion pool at designated locations. Note that upslope hydraulic considerations must account for melting of potential annual snowpack, in addition to any perennial drainage networks and erosion control measures.

2. Internal Seepage Control – Consists of installation of drilled drains (or upslope well points) to permit seepage of fracture controlled water flow, which may help to drain water within the rock mass; however, our experience with these is that slope drains are intended for dewatering potentially unstable rock masses, and that these elements can become clogged under even the best of circumstances. We have seen instances where ice has plugged the outlet of these upward-battered drainage pipes, which could induce rock slope instabilities. These features may also draw-in far-field water from upgradient. For this reason, ***we do not expect internal seepage control to be a viable option for the reduction of ice volume***.

8.3 Ice Removal Options

Ice scaling methods could be used to remove the hazard from the highway slopes; however, this may be challenging when the ice has developed full ice-rock contact adhesive strength. On the contrary, if scaling were to commence during periods of higher temperatures, it may be considered risky even for experienced operators and rock remediation technicians as access and control of falling material could be difficult to achieve. Direct ice removal methods include:

1. Blasting Methods – Roadway would require temporary closure to use light charges and "shoot" off ice slabs. Use of this method would require access to top, likely using rope access techniques, which would be risky to the slope technician. This technique was used successfully by Alaska Railroad Corp. to remove potentially unstable stabs above the railway; however, apparently the efforts were not easy. ***Given the risky nature of this approach and expected traffic stoppages, use of blasting methods along highways is not expected to be widespread*** but could be used in extenuating circumstances.

2. Manual (Light) Scaling Methods – Would consist of light equipment (scaling bars, saw for cutting, etc.) utilized via rope access techniques or man-lifts. The use of air bags would also be beneficial to manual removal of ice slabs, especially around the perimeter of slabs which will tend to melt first. ***Manual scaling is a risky approach*** as the ice is difficult to both access (i.e. climb) and remove at the same time. This method is seen as being secondary to other methods described and would likely be most suitable for removal of relatively small (e.g. generally <5 ft. dia.) ice blocks that have already melted-back significantly.

3. Machine (Heavy) Scaling – This approach has lots of potential for ice slab removal, especially during periods of rapid melting and concern for short-term instability. ***Removal of ice using construction equipment staged from bottom of slope is considered highly risky, and is not recommended*** unless the slab is relatively small and the operator can access at an oblique angle from side with a long arm excavator or a hoe ram (pick hammer). Large or high ice slabs could be removed with a steel "Slusher" frame, which is used in the mining industry to scale benches (Fig. 17). The device has teeth in the front and is run from a remote location using cables and a wench assembly. Alternatively, the similar device could be suspended from a helicopter and used to knock the ice off of the slope face.

Figure 17 *– Picture of "slusher" scraping the slope of loose debris (Photo by Ameritech Slope Constructors, Inc.)*

4. Alternative Scaling Method: Pre-Installed Air Bags – This approach was suggested to us during our conversations with a specialty rockfall mitigation contractor and we thought it merited presentation. The concept includes installation of “packers” (inflatable air bags used during rock scaling) on the slope face where ice frequently builds. The system is filled with ethylene glycol (i.e. antifreeze solution) so that it works in sub-freezing temperatures. When the ice reaches a certain maximum thickness, the air bags are inflated from a remote position (likely hundreds of feet away) so that the ice is scaled off the slope face. The system could be triggered by DOT&PF staff after training on use. The down-sides of using this alternative include the following:

   - Roadway needs to be temporarily shut-down during scaling;
   - Approach using air bags for ice has not been attempted before;
   - Possible damage by rock and ice climbers;
   - Possible release of small quantities of antifreeze if damaged;
   - Risk that ice does not develop where expected; however, at specific locations there may be enough data to support consistent ice development;
   - Need “trigger” or threshold for immediate action – for example, once rock slope surface temperatures exceed 32 deg. F, would require human triggering of air bars

Another disadvantage of the ice removal options that would need to be considered is the potential to damage the underlying rock slope, which could result in an increase the frequency of rockfall events. One final consideration is that M&O would need to have qualified and experienced rock slope remediation technicians (with all required equipment) nearby or even on stand-by.

8.4 Traffic Pattern Modifications

Traffic pattern modifications could be very useful as both a temporary and permanent icefall hazard mitigation measure:

***Figure 18** – Traffic pattern modification and detour at MP 113.2 area (Photo by Alaska DOT&PF)*

1. Temporary Traffic Modifications – Would be a short-term solution to a perceived imminent icefall impact risk, and one that could be deployed relatively quickly. For example, there is already a temporary traffic diversion and lane closure plan in the area of MP 113 – we saw this implemented after we reported small icefall sloughing events on 20 March 2017, including use of appropriate advance signage. Traffic is slowed down due to the temporary lane changes but this approach afforded an additional lane of offset between northbound traffic and the bottom of the slope. A similar approach could be drafted-up for other locations as-needed based on projected site-specific impact area limits and available space within the roadway section. One down-side to use

of temporary traffic modifications is that the M&O field crews are exposed for a period of time (usually hours) while they are setting up and maintaining the diversion.

Temporary traffic pattern modifications could be utilized on a semi-perminant basis during periods when the probability of thawing conditions is expected based on weather forecasts; or when active ice sloughing is observed. Longer-term barrier deployment periods (measured in weeks or even a month) may require reconsideration of "standard" distances shown in traffic diversions/detours, including number of lanes taken. Years with extreme ice slab thicknesses could require site-specific revisions to standard diversion plans.

2. <u>Permanent Highway Layout Modification</u> – ***Permanent highway layout alterations would be highly effective at mitigating icefall hazards assuming there is existing horizontal width within the highway's geometric section***. If there's insufficient width to modify use of existing limits (e.g. adjacent waterway or another slope on other side of highway) or to expand catchment width, then there may be large-scale changes to site grading (i.e. slope excavation) required before this option could be implemented.

8.5 Major Site Regrading Efforts

Re-grading efforts would consist of major alterations to the site topography which would impact drainage, highway layout and slope limits. These improvements would be highly effective at mitigating the long-term icefall hazard but would be expensive and time consuming and would require use of temporary traffic pattern alterations during the work. Such options would include:

1. <u>Slope Re-Grade</u> – This approach would require mass excavation of the rock slope and would likely make use of controlled blasting methods (including use of perimeter control methods). Intent would be push the slope back far enough to create increased catchment width at the toe and afford additional offset between slope and roadway. This approach would also allow for upslope surface water drainage path alterations. Similar to any new cut, the slope also would need to be designed with rockfall catchment and global stability in mind. ***Slope re-grading is a <u>highly effective</u> way to mitigate the icefall hazard***; however, the expense and temporary traffic impacts could be considerable.

8.6 Icefall Mitigation Structures

Installation of icefall mitigation structures would include the use of designed and traditionally installed rockfall mitigation elements to limit the horizontal displacement of falling ice slabs. Based on our extensive research, there are not many examples where rockfall mitigation elements have been used to arrest falling ice hazards; however, there are a few examples as describe further below:

1. <u>Use of Rockfall Barriers</u> – Rockfall barriers (Fig. 19) can be designed to effectively capture icefall; however, to-date there are no documented examples where icefall barriers have been designed or deployed for icefall hazards alone. Design of the flexible netting suspended between posts would consider deflection, offset location and kinetic energy requirements; however, netting aperture size can also be designed to capture ice fragments cast outward from secondary impact shatter events. Preliminary icefall barrier studies were completed by the author (*2*) in Maine in 2012 but were never implemented. Note that the benefit of using barriers is also extended to the site if rockfall is an ongoing problem, but barrier min/max impact energy and deflection criteria must consider rockfall as barriers are considered permanent features. One key element of

consideration with barriers is horizontal location – if barrier is to closet to highway, the system could deflect into oncoming traffic. On the other hand, if the barrier is too close to the slope, falling ice could overshoot the barrier and enter the roadway. ***Horizontal placement of proposed barrier limits is the single most important factor in conceptual preliminary evaluations of barrier effectiveness***. In other words, if there is no room in the highway section to accommodate both system deflection and maximum icefall trajectory, then barriers may not be a realistic solution.

2. <u>Rockfall Netting</u> – Rockfall netting could be employed as draped or partially-anchored system at sites subject to icefall. There are three specific locations where we are aware of netting being used to manage icefall hazards, those being in Germany, Norway and Austria:

Figure 19 *– Slotted icefall netting & upslope flexible barrier in Austria (Photo by Trumer, Ltd.)*

   - In Germany, high-strength rockfall netting was used a drape suspended from hinged posts at the top of the slope according to a case study by Geobrugg. According to the case study, it appears the system worked as intended; however, the ice volume that was developed behind the netting appears to be very small (significantly less than MP 113 for example). It is unclear how a traditional top-supported drape would perform under the influence of large ice slabs, but small slabs could likely be managed with conventional rockfall drapery.

Figure 20 *– Slotted icefall netting used in Austria (Photo by Trumer, Ltd.)*

   - In Norwegian and Austrian Ministries of Transportation permitted designers to utilize a “slotted” netting approach as shown in Figs. 19 and 20, whereby high-strength netting is used with steel bar “stand-offs”. The bars permitted the netting to be installed at a distance between 3 and 5 ft. from the rock slope, which in turn creates a slot for ice to develop and subsequently fall during periods of melting. Based on the limited information we obtained, it does appear that design criteria included maximum ice thickness and maximum failure block size. ***The primary risk with use of a netted icefall slot is with underestimation of ice thickness, which could result in the entire system being compromised.*** Use of a designed icefall slot required firm data on annual ice thickness and maximum probable ice thickness and width. Small to medium-size slabs could likely be managed with a slotted netting approach. We understand that the European systems described above were primarily designed to handle ice blocks falling from above the slope crest – not falling directly from the slope face.

3. Alternative Use of Netting: Pre-Hung Drapery – An additional use of netting that could be considered is pre-installed netting at the top of the slope face. This would allow the netting to be installed during non-winter months and deployed over the slope face and ice slab at the onset of suspected unstable behavior. The netting could have local aesthetic implications (colorized options exist for netting) but the system would be temporary (late winter) and could be placed back at the top of the slope after ice melt back. It should be noted that this has not been attempted before with icefall mitigation; however, the industry routinely used netting for temporary rockfall application so we believe this approach could work. The intent of the pre-hung drapery would be to restrict the horizontal (outward) component of ice slab movement and to contain falling ice debris. The netting may need to be drilled at the crest of the slope and/or placed in a container to ensure that it does not get frozen. The drapery could be installed using rock remediation technicians and/or a helicopter (possibly even a crane with enough boom length and capacity). Once in place, a local contractor with rope access experience could deploy and retract (i.e. roll-up) the system on yearly or as-needed basis. Netting could be damaged by extensive loads, so strength, capacity and anchorage components would require submission of formal design calculations and plans. Periodic maintenance or even re-installation of anchors may be required over the long-term. Furthermore, ice could redevelop and adhere to the outside of the netting during alternating freeze-thaw cycles. In our opinion, ***this alternative netting solution would be highly effective but there are significant challenges with deployment as an experienced contractor would need to be on "stand-by"***.

4. "Reinforced Ice" - Could install steel (or possibly fiberglass as it heats-up less than steel) bars (e.g. rock bolt material) perpendicular or angled to the face (during summer) to interface so bars mobilize shear resistance, resist bending and inhibit movement. This solution would be relatively cost efficient in comparison to others and would not require more than a few weeks to construct, assuming an experienced contractor was retained. Downsides to this approach include the fact the fact that this method has not yet been used for ice slab sliding resistance and that it may have aesthetic (visual) impacts during non-winter months. It could also present a hazard to ice climbers. ***This is a solution worthy of further consideration***.

5. Rockfall Shed – This type of feature is used in Europe for rockfall mitigation applications and can be thought of as being similar to a covered bridge. A three-sided structure would be built onsite or prefabricated in sections and erected at the site. The frame is designed to take impacts from falling materials like rocks, ice and snow loads. Aesthetically pleasing features can be included to minimize visual impacts to the area.

6. Jersey Type Concrete Barriers – Concrete Jersey type barriers could be used as a measure to control shatter from an impact event. Jersey barriers should only be installed directly adjacent to specific areas of observed ice slab development. Barrier line would be extended beyond the estimated lateral limits of each ice slab. Side impact from vehicles would need to be considered if close to roadway. Follow the Manual on Uniform Traffic Control Devices (MUCTD) for appropriate temporary signing of the hazard.

8.7 Other Potential Solutions

During development of potential icefall mitigation solutions, we wanted to present some other possible mitigation strategies that were considered but that require additional research prior to use:

- Accelerated melting - Either through use of thermal or chemical methods; however, chemical application could pose environmental impacts;
- Application of heated rockfall netting or mesh - This could be developed long-term but is not available for immediate use;
- Provide for additional internal reinforcement using mesh inside the ice (parallel to ice flow and slope) so that it develops around the netting and develops increased internal tensile strength. Could be used in conjunction with “reinforced ice” option noted above;
- Installation of ultra-low adhesive bonding material for minimal ice buildup (e.g. Teflon);
- Research test section – Instrument and monitor one specific location like an icefall hazard test section (possibly MP113).

Note that permanent signage could also be considered, making use of signs that state “falling debris” or “falling ice”; however, some DOT’s do not like this approach. In addition, signage could be considered for keeping (or attempting to keep) the public from standing below (or climbing on) the slope.

SECTION 9 – SITE-SPECIFIC EVALUATIONS & RECOMMENDATIONS

This final section of the report contains condensed information specific to each of the seven study sites along the Seward and Richardson Highways. Each subsection contains the results of field studies, icefall technical evaluations and summarizes recommendations for location-specific mitigation solutions worthy of consideration.

9.1 Initial Site Screening

Our technical evaluations consisted to a two-phase approach. As introduced in Sec. 6.6, the first phase was characterized by an initial "screening" evaluation to provide a way to differentiate impact risk at each of the seven sites, as each site has unique qualities. The screening evaluation results are summarized in Table 2 below and the full table entitled *Preliminary Icefall Impact Risk Matrix* (PIIRM) is included as Appendix 4. The table demonstrates that there are three specific sites with an elevated level of icefall risk to the roadway, those being MP 113.1 to 113.3 NB Seward Highway ("High"); MP 13.7 to 14.0 SB Richardson Highway ("Moderate to High"); and, MP 51.9 to 52.1 ("Low to Moderate"). The other four sites may develop icefall hazards and impart periodic (yet less frequent) icefall impact risks from year-to-year; however, these four sites tended to have significant catchment ditch widths with respect to slope height and unobstructed sight distances. So while the icefall hazard may exist, the actual impact risk to the highway is expected to be relatively low.

The attached table helped us understand what sites needed detailed evaluation and which sites required a less detailed approach as they present significantly lower risk to the roadway and those using it. Lower risk sites were subject to less rigorous technical evaluations. On the other hand, if preliminary screening indicated a higher risk bracket, then the technical approach and array of potential icefall mitigation options will be more detailed at that specific site. Use of the table does not imply that we excluded low risk sites from further consideration, but rather that we tailored our studies around those sites that present elevated risk to the travelling public. This approach allowed us to weight our technical efforts on sites with an initial risk level that was elevated, and we used this approach as a basis for development of the PIIRM.

TABLE 2
Abbreviated Prelim. Risk Ranking by Site

Site	Prelim. Risk Ranking
MP 113.1 – MP113.3 SEW	HIGH
MP 74.1 – MP 74.9 SEW	LOW
MP 57.9 – MP 58.2 SEW	LOW
MP 51.9 – MP 52.3 SEW	LOW-MOD
MP 38.3 – MP 38.5 RICH	LOW
MP 22.7 – MP 23.3 RICH	LOW
MP 13.7 – MP 14.0 RICH	MOD-HIGH

The second phase of technical evaluation consisted of more detailed analyses as indicated in the following sections below, dependent upon results from the initial screening evaluation. Technical evaluations at sites of "low risk" to the highway consisted of geometric evaluations only. Sites with an expected elevated level of risk (i.e. “Moderate” and “High”) required technical evaluations which were more rigorous, in addition to the geometric analyses completed for the other “Low” risk sites. The types of evaluations we completed consisted of the following:

A. Simple Geometric Analyses – Assessment and comparison of observed (and probable) ice slab dimensions and roadway and catchment dimensions. Considered probable mechanisms of failure for falling, sliding or rotating slabs based on geometry. This includes geometric evaluation of known previous failure events;
B. Sliding Ice Block Analysis – Used equivalent rock block sliding approach using industry-available planar sliding analysis software called *RocPlane©* from Rocscience, Inc. The model runs allowed us to complete evaluations of ice-rock contact shear strength, including sensitivity analyses relative to adhesion strength and slope roughness.
C. Icefall Impact & Force Analysis – Included developing estimates of icefall weight, impact force and energy. Where possible, we attempted to “back-analyze” previous failure events to understand the magnitude of future icefall impacts.

Although we collected and assessed data within the entire interval of each site, we also looked at subsections within each interval based on the locations of observed water flow in September 2016 and ice slab growth in March 2017. We refer to these subsections as “Critical Sections” in the tables included as Appendix 5, and have completed the technical evaluations shown below at each of these specific locations. The critical sections are seen as being representative of the most likely location for the icefall hazard to develop within each interval.

To summarize, we collected data during both summer and winter conditions, and had the benefit of seeing ice development while completing our March 2017 site visit. Based on our understanding of the seven sites (i.e. histories and site geometry provided by DOT&PF) and our direct onsite observations, it is apparent that the ***MP 113.1 – 113.3 area along the Seward Highway is the most critical in terms of potential icefall hazards and subsequent risk posed to the traveling public***. We also note that ***MP 13.7 to MP 14 along the Richardson Highway has the potential to periodically generate damaging icefall.*** On the other end of the spectrum, the other five sites appear to present minimal risk to the travelling public based on the geometry of the roadway, adequate sight distances, and catchment available for falling ice fragments. The site-specific details associated with each of the seven sites is described in detail below.

9.2 Site-Specific Icefall Histories

Site icefall history is a critical indicator of potential for future icefall events, and would generally include event date(s) and time(s), location, frequency, and event “size” (approx. dimensions or volume of post-failure debris). Our understanding is that three of the seven sites have experienced icefall direct impacts to the roadway, with one other site having experienced ice shatter throw. Based on results from Phase No. 1, our direct observations in the field and periodic feedback from DOT&PF staff, we prepared a brief summary of documented location-specific icefall events. Note that icefall events are likely occurring more frequently than observed, given the following:

- Ice development and duration is transient in nature and is subject to rapid degradation via melting and mechanical comminution (e.g. run over and broken-up by vehicular traffic);
- Falling ice may be maintained within roadside ditches and not generally observable to public;

- Psychological aspects where people tend to be more prone to reporting fallen rock or trees but not so much snow and ice which may be considered “routine” observations for those folks travelling Alaska’s highways;
- Falling ice is not always easily observed by motorists given fall location, event size and translucent to white color;
- Many locations may be remote and subject to relatively low Average Daily Traffic (ADT);
- There is no established criteria (yet) for how to track, manage or monitor fallen ice pieces.

Based on documented icefall events in Alaska, a summary of observed (i.e. measured) and estimated (from pictures and personal accounts) direct impact and ice shatter throw distances by location in included in Table 3 below.

TABLE 3
Estimated Impact Distances

RECORDED EVENTS			ICE HEIGHT ABOVE ROAD(FT.)	PRIMARY IMPACTS			SECONDARY IMPACTS			
				DIRECT IMPACT(1) DISTANCE (FT.)			SHATTER DISTANCE (FT.)			SPLATTER (FT.)
MP	TYPE	DATE	MAX	MIN	MAX	AV.	MIN	MAX	AV.	MAX
113.2 SEW	SLIDE/FALL	4/16/2012	80	0	22	11	0	35	18	U
113.2 SEW	FALL	3/20/2017	85	4	6	5	6	55	31	N.O.
52.0 SEW	SLIDE	U	U	23	52	38	U	U	U	U
52.0 SEW	SLIDE	U	U	0	24	12	U	U	U	U
23.0 RICH	SLIDE/FALL	U	33	U	U	U	0	46	23	U
13.9 RICH	LOCAL TOPPLE/FALL	12/13/2017	20	4	22	13	22	54	38	N.O.

(Note: “U” is unknown and “N.O.” is not observed.)

MP 113 Area Seward Highway

Mile Post (MP) 113 northbound (east side of highway) is a unique area given the history of icefall (and rockfall) at the site. Most notably, a large slab of ice fell and injured a passing motorist adjacent to MP 113.2 on the afternoon of Friday, 6 April 2012. The falling slab was estimated to be on the order of 60 ft. to 80 ft. in height by 20 ft. in width and resulted in direct impact to a small truck, crushing the vehicle and its occupant (Fig. Nos. 1 and 21). According to media reports, ice had been falling from other portions of the slope earlier that same day, so it appears that a smaller section of the approx. 100-ft. long overall ice slab peeled away from the slope. Based on recorded weather conditions (Appendix 3), there was an extended period of warming between 28 March and 6 April 2012 where average daily temperatures were above the freezing point. The slope surface is thought to have warmed rapidly enough to allow for de-bonding of the ice slab through loss of ice-rock interface adhesive strength. This loss of adhesive bonding along the ice-rock contact deprived the ice slab of the interface strength needed to support its own weight. It is thought that the lower portion of the slab gave way first, which removed support for the upper slab and resulted in a large ice slab failure event.

Figure 21 – *Clean-up of 6 April 2012 icefall event near MP 113.2 on the Seward Highway (Photo by KTUU)*

Other smaller ice shedding events have occurred at MP 113.1 to MP 113.3 since the 6 April 2012 event. On 13 March 2017 we observed small pieces of ice less than 12 in. diameter that had recently fallen into the small roadside ditch. We also observed small pieces of ice being shed into the ditch and onto the highway on the afternoon of 20 March 2017 (Fig. 12). Although maximum air temperature was measured at 27 deg. F, the solar intensity was high on 20 March, resulting in heating of the south-facing rock slope surface. Water was observed dripping in multiple locations due to active ice melting and water vapor was also seen emanating from the dark-colored slope surface. On average, we observed one piece of ice (< 12-in. dia.) falling every 30 to 60 sec. Ice fragments appeared to be sloughing from the bottom upwards. One portion of the ice slab measuring approx. 8 ft. high by 3 ft. wide by 1.5 ft. thick appeared to be partially detached (de-bonded) from the slope surface. We also observed two small rockfall events (approx. 6-in. dia.) originating from mid-slope height just below the bottom of the remaining ice. The rockfall source area surface was fully-saturated from melting ice above; however, the small roadside ditch maintained both rockfall events. An ice block measuring approx. 2 ft. in max. dimension fell at approx. 16:15 hrs. on 20 March, resulting in ice shatter upon direct impact with the ditch. The impact shatter threw a 5-in. fragment of ice (Fig. 14) approx. 55-ft southwesterly across both lanes of the Seward Highway. (Note: We notified DOT&PF about the active ice shedding events on the afternoon of 20 March 2017, and a traffic diversion pattern was set-up within the normal response time to establish an additional lane width of horizontal offset distance from the slope toe)

MP 52 Area Seward Highway

The segment of slope at approx. MP 52.2 to 52.3 southbound (west side of road) has been known to develop ice and on occasion has even produced sliding ice slabs affectionately referred to by DOT&PF staff as "Belugas" given their size. Apparently, these Beluga-sized ice blocks had made it some distance into the active roadway. We were also informed that a sliding ice slab pushed down a small roadway sign at MP 52. We are not aware of the specific timing and exact location of either of these events noted above. While onsite on 20 March 2017, ice was well-developed at MP 52.25; however, there was no sign of ice melting or slab instability at the time of our visit.

MP 23 Area Richardson Highway

According to DOT&PF Valdez District M&O staff, the area between approx. MP 22.8 and 23.3 at Thompson Pass has periodically had small chunks of ice shatter end up on the paved shoulder adjacent to the fog line. We are not aware of any other specifics of these relatively small, nuisance icefall events. We visited the site on 16 March 2017 and observed significant yet localized areas of ice development; however, given the very cold temperatures, evidence of ice instability was not observed.

MP 14 Area Richardson Highway

The portion of slope between approx. MP 13.7 and 14.0 southbound (west side of road) in Keystone Canyon has periodically shed small to medium blocks of ice, based on observations provided by DOT&PF Valdez District M&O staff. One specific segment of slope at approx. MP 13.9 is referred to by staff as “Car Wash Rock”, as there is frequently running surface water cascading over the slope face. There was very limited ice development on 15 March 2017 when we visited the site.

Figure 22 *– Photo of 13 December 2017 icefall event near MP 13.9 on the Richardson Highway (Photo by Alaska DOT&PF)*

More recently, there was an icefall event documented by Valdez M&O staff on 13 December 2017 as shown in Fig. Nos. 8 and 22, due in part to heavy local snowfall (and subsequent melting-refreezing) the first week of December. This event appears to have occurred at approx. MP 13.9 and covered both lanes of the road width ice debris to a width of approx. 8 to 10 ft. The slab appears to have been approx. 2 to 3 ft. thick and based on photos provided by M&O staff, the total volume of the ice failure event appeared to between approx. 15 and 20 c.y. The ice slab was apparently adhered to the edge (top) of the rock slope and appears to have been subject to local toppling (rotation) based on observed final failure limits. Whether the ice slab fell and then rotated or was subject to direct rotation at the moment of incipient failure is unclear. It also appears that the slab direct impact was at approx. 22 ft. from toe of slope (at edge shoulder) and comprised the ditch, shoulder and a portion of the southbound travel lane, with approx. 10 to 20% of the volume being cast across the road as impact shatter. Based on our site observations, it appears that the lower 20 ft. of rock slope is locally overhung by 3 to 5 ft., rendering the catchment ditch only partially effective. There were no injuries or direct vehicle impacts associated with this specific event, but a slab failure of this size would constitute a clear hazard to the roadway and those using it.

9.3 Comparisons of Observed Ice Development

Based on our site observations, we can draw some preliminary comparisons relative to ice growth. Well-developed ice formations were observed at six out of the seven sites (86%). This included a total of 17 well-developed ice formations, as there were multiple discrete formations at certain sites. Ice coverage areas within the lateral extents described herein varied between <1% of the exposed slope surface (MP 14 Richardson Highway) to as much as 13.3% (MP 52 Seward Highway), as shown in Appendix No. 2.

All of the well-developed slabs appeared to have been formed from the freezing of upslope water as it was intercepted by the slope face. Direct impact by precipitation (e.g. snow, rain) falling on the slope face did not appear to be a major source for significant ice development. Presence of fracture-controlled seepage appeared to be less significant in the development of ice than direct overflow of upslope surface water over the crest of the rock slopes, based on the following site observations:

- surface water discharge locations observed in September of 2016 were in close proximity to major ice features observed in March of 2017;
- Trickling water was heard behind (or within) major ice slabs observed in March 2017;
- Ice formation morphology (vertical columns or spires fused together) suggests steady-state source of water available for consistent cascading, freezing and outward growth of ice crystals;
- Re-freezing of upslope water generated from snow melt also appeared to be a causative factor in the addition of surface water to the slope system;
- Ice was found to have a blue hue at four of the seven sites (57%), which includes eight of the 17 (47%) specific ice slab features witnessed in March 2017. The blue hue indicates relatively thick ice growth as light is diffracted through the ice medium, and thickness is an indication of consistent addition of water.

Although joint-controlled seepage appeared to add to the development of ice slabs, in most instances it did not appear to not supply the volume of water needed to generate large formations.

9.4 Key Parameters

As part of Task No. 2 technical analyses, we evaluated potential icefall hazards at each of the seven candidate sites, based on the following sources of information:

A. Information from the Phase No. 1 Literature Review, including roadway construction as-built plans;
B. Site-specific observations, photos, and data collected during Phase No. 2, Task Nos. 1A and 1B. Field data from both visits is included as Appendices No. 1 and 2;
C. Photos, data, and information from specific ice failure events such as the 6 April 2012 Seward Highway icefall event and the 13 December 2017 icefall event along the Richardson Highway;
D. Photos and email information from DOT&PF M&O and Engineering Geological staff of ice development conditions at various sites prior to April 2017;

We selected properties and parameters needed to evaluate and model ice slab failure mechanisms, which included the following:

- Slope angle (ice-rock contact angle) – site specific;
- Slope height – site specific;
- Ice slab dimensions (length, width, height) – site specific;
- Slab face angle – site specific;
- Adhesive shear strength (min/max) – assumed 75 psi (0.5 MPa)/150 psi (1.0 MPa) at 0° C;
- Adhesion tensile strength (min/max) – assumed 35 psi (0.25 MPa)/75 psi (0.5 MPa) at 0° C;
- Ice cohesion value – assumed 0 psf;
- Freshwater ice unit weight - assume 57.2 pcf (916 kg/c.m.) based on literature;
- Ice-rock interface base friction value ($\emptyset_b$) - assumed 0 deg.;
- Ice-rock large-scale roughness friction (i) – site specific;
- Temperature of air & bedrock surface – site specific

These values were used where appropriate based on preliminary screening risk assessment to complete ice slab sliding sensitivity analyses and to estimate ice block impact energy-force characteristics.

9.5 MP 113.1 to 113.3 NB Seward Highway

Site Observations

Figure 23 *– Photo of ice conditions near MP 113.2 on 13 March 2017 (Photo by Scarptec, Inc.)*

The site is comprised of a steeply cut south-southwest facing rock slope with slope heights ranging between 50 and 140 ft. Existing slope angles range between 70 and 86 deg. based on direct measurements of the slope; however based on available as-built plans, it appears that the slope is generally between 76 deg. (4V:1H) and 82 deg. (8V:1H). The slope appears to have been cut in "lifts", resulting in small lineations or remnant benches at approx. 30 ft. height intervals. These remnant benches provide efficient ice support ledges where ice can "hang-on" and support overlying upper slabs. Free water in the form of surface and fracture-controlled discharge is abundant at this site due primarily to upslope run-off from snow melt. Natural surface water drainage channels exist at the top of the slope, as witnessed in September 2016. As-built plans show 40-ft. long near-horizontal slope drains installed at the base of this slope. The available (i.e. "effective") catchment width between the toe of the slope and the paved shoulder is very limited, and on the order of 8 to 14 ft. based on our measurements (as-built plans show 10-ft. catchment width). Ditch depth ranges between 0 and 3 ft. depending on specific location. The sight distance available to motorists along this two-lane (12-ft. ea. lane) stretch of highway is on the order of 1,250 ft. and is generally sufficient to observe debris which is already in the roadway. There is also a 41-ft. wide viewing turn-out available for temporary lane closures or traffic pattern changes through a majority of the affected area, resulting in a total paved roadway width of approx. 90 ft. Data collected during the September 2016 visit is included as Appendix 1.

While onsite in March, we observed an area of developed ice at approx. MP 113.2 as shown in Fig. Nos. 23 and 24. Given the site's close proximity to Anchorage, we had the opportunity to observe the slope on multiple occasions. The ice slab was approx. 43 ft. in height by 26 ft. wide by 1 to 6 ft. in thickness based on measurements obtained with a laser range finder on 13 March, as shown in Appendix No. 2. We also observed small-scale (< 24 in. dia.) sloughing of ice fragments during our site visit, as the ice appeared to be melting back over the week due to rock slope heating from long periods of direct sunlight. (Note: Based on our Phase No. 1 Literature review, we understand that ice within this section has historically been much more significant in thickness and extent and that this area is frequented by the ice climbers. The observed ice size estimates should be used with caution as ice slab dimensions could vary extensively over time)

Given our site observations relative to the limited catchment width available, abundance of upslope water, presence of remnant benches, ice development frequency, site icefall history, and relatively high traffic volume, MP 113.1 to 113.3 is expected to present a long-term icefall hazard to motorists during the winter and spring months along this stretch of the Seward Highway.

Figure 24 *– Ice conditions along ditch near MP 113.2 on 13 March 2017 (Photo by Scarptec, Inc.)*

Technical Evaluations

As shown in Table 2, the ***MP 113.1 to 113.3 NB site was regarded as having a "High" level of risk*** from potential icefall impacts, as further evidenced by the 6 April 2012 icefall event along the Seward Highway that resulted in significant injuries to a motorist. This event can be considered as a "design basis scenario" for mitigation of future icefall hazards along this section of roadway.

Geometric Analyses

We completed geometric evaluations based on slope height, ditch width and roadway width, as reflected in Appendix 5. Simple geometric analyses indicate the following findings:

1. Width of the catchment ditch from MP 113.1 to 113.3 is insufficient with respect to capture of potential icefall events. The existing catchment is between 8 and 14 ft. in overall width with slopes between 50 and 140 ft. in height. This is further confirmed by our onsite observations in Table 3 showing that even small shatter events can be thrown across both lanes of the highway. (Note: This fact is also likely to apply to rockfall hazards falling from the slope face – we understand this segment of highway subject to periodic rockfall.
2. The distance from slope toe to centerline of road (dividing line between lanes) is approx. 29 ft., resulting in a roadway that is too close to the slope. The closer the highway is to the slope, the higher the likelihood of direct impact events. Based on information from the 6 April 2012 icefall event, we estimated that the area of direct impact extended out approx. 22 ft. from toe of slope, which is within the northbound travel lane.
3. Based on the estimated volume ice of the 6 April 2012 icefall event, the available volume of the roadside ditch is inadequate for retention of fallen ice even if all the ice fell directly into the ditch.
4. This site is unique with respect to the other six sites, as the AADT is significantly larger (by upwards of three times) and the slope-parallel width of ice development can approach us much as 80 to 100 ft. The extensive ice development width can result in multiple ice shedding events throughout the effected interval.
5. In addition to the direct impact risk that exists at this site over the winter and early spring months, secondary impact shatter events could also periodically enter the roadway when icefall does occur.

Sliding Ice Block Analysis

We completed sensitivity analyses for ice sliding from loss of adhesive strength along ice-rock contact surfaces using *RocPlane* from Rocscience©. Although this is ideally intended for use with rock block sliding along an inclined plane, we assumed an equivalent rock block approach for sliding ice blocks, as the mechanics are similar. We used an interface adhesion shear strength value of 75 psi (0.5 MPa), along with the other input parameters shown above in Sec. 9.4. What we found was that frictional properties, as expected, play a very small role in contributing to stability of sliding ice blocks. At temperatures approaching 32 deg. F (0 deg. C), the base ice friction angle (ϕ_b) is approx. 2 deg. which is very low. In addition, large-scale roughness did not play a significant role in development of shear resistance along the slide plane. Based on this, we chose to be "conservative" and assume that frictional component of shear resistance is essentially zero. This is not an unreasonable approach, given that adhesion strength will be the dominant control on shear resistance at the moment of failure. This simplified the model and allowed us to focus on the major factor in ice slab stability – adhesion strength.

Factor of Safety (FS) is defined as the ratio of those forces resisting instability to those forces inducing ("driving") instability. This deterministic approach is frequently used with slope stability analyses, especially with preliminary studies. As described in Sec. 4.3, the shear strength along the ice-rock contact will be dominated by adhesive strength. If we use a relatively low end value cited in the literature for adhesive shear strength 75 psi (10,800 pounds per sq. ft.) and assume this is essentially a constant, then the intrinsic adhesion value per unit area during times of stability is the same during times of instability – meaning that failure will commence when the available adhesive contact area is minimized due to melting.

Loss of adhesive bond contact area due to melting will result in a reduction of ice slab shear resistance. This observation is unique to ice, as geotechnical slope stability analyses usually assume a relatively constant adhesive (or cohesive) contact area, but ***because ice is subject to melting, the contact area is actually reduced as the system tends toward instability***. To assess the loss of net adhesive area at failure, we ran two separate analyses. We started with an initial adhesive shear strength of 10,800 psf, which resulted in safety factors that were very high as expected. We then "destabilized" the system by setting the FS equivalent to approx. 1.0, whereby the ice block is considered meta-stable and at the point of sliding. The required minimum shear strength along the slide plane at the onset of failure was found to be approx. 300 psf; however, the loss of contact area makes this an "apparent" adhesive strength. Because adhesion strength is assumed to be a constant property of ice at temperatures close to freezing, we back-calculated the loss of adhesive contact area using Eqs. 6 and 7 and found that there was a reduction of 96.8%. Results of these analyses are included as Appendix No. 6. This means that at the onset of slab sliding, only 3.2% of the initial adhesive contact area was still intact. Using simple ratios of adhesive strength, which has units of stress or pressure:

$$\frac{F_{Ad}}{A_1} = A_{Ad} = \frac{W_{ICE}}{A_2} \qquad \text{(Eq. 6)}$$

$$A_2 = \frac{W_{ICE}}{A_{Ad}} \qquad \text{(Eq. 7)}$$

Where, A_{Ad} is adhesive shear strength, F_{Ad} is adhesive shear resistance force, W_{ice} is weight force of the ice block and A_1 and A_2 are stable (initial) and metastable (at failure) adhesive contact areas, respectively.

The preceding evaluation shows that ***adhesive contact area reductions of as much as approx. 95% of the initial contact area may still support a slab of ice***. These small adhesive "bridges" will support the ice until the contact area is further reduced, resulting in failure. This evaluation undoubtedly simplifies the physical situation, as there is a small frictional component that adds to the net shear resistance and this component becomes more significant as the slope angle is reduced; however, at most sites we inspected (including MP 113), slope angles were high which reduces the significance of the frictional resistance at the onset of failure.

The key takeaways from this evaluation include the following:

1. ***Loss of apparent adhesive strength is actually due to loss of adhesive contact area, which is directly related to an increase in ice-rock interface temperature***, with the bedrock surface heating up faster than the surrounding air mass due to solar radiation;
2. ***Even relatively small adhesive ice-rock contact "bridges" will support an ice slab*** given its relatively low density. The ice slab is also subject to melting internally, and so total weight is likely being reduced at the same time that the interface is melting; however, the interface is expected to melt faster than the overall ice mass given rock's higher coefficient of thermal conductivity;
3. Icefall events resulting from ice slab failures on the slope face do not happen instantaneously. ***Slab failure takes consistent input of direct solar radiation heating the ice-rock interface to temperatures at and above freezing***.

Post-Failure Impact Energy & Force

Figure 25 *– Damaged vehicle from 6 April 2012 icefall event near MP 113.2 on the Seward Highway (Photo by KTUU)*

By our estimates based on photos, the falling slab of ice was approx. 60 to 80 ft. high by 20 ft. wide by 4 to 6 ft. thick. It appears that the direct impact zone extended approx. 22 ft. from toe of slope and maximum lateral extent of ice debris field was approx. 35 ft. from the slope toe (Fig. Nos. 1 & 21), just beyond the centerline of the road into southbound lane. It also appears that the this specific ice sheet failed in discrete sections, as there appeared to be other slabs that came down at different times. Based on our site observations, photographic evidence and recorded accounts from that day, we believe that the slab ultimately failed by loss of adhesive shear strength along the rock-ice contact in a period of increased average daily temperatures, resulting is a large cascading mass of falling ice. The failure event was likely a prolonged direct impact event lasting between 3 and 6 seconds as ice fell on itself and was subject to self-crushing at impact. In other words, this was not one discrete block but rather a series of slabs that delaminated vertically up the slope face. This resulted in significant damage to a small sports utility pickup truck (e.g. Ford® Ranger or equivalent), and it appears from photos that the truck was compressed vertically between 2.5 and 3.5 ft., as indicated in Fig. 25 above.

We estimated the impact force and energy of the 6 April 2012 event based on post-accident photos of the damaged vehicle and the ice blocks, with the full tabulation included in Appendix 7. An abbreviated version of the results is provided as Table 4 below. This analysis used kinematic equations for vertical fall of an equivalent ice block weighing 22.3 kips falling from an average distance (to center of mass) of 45 ft., and of equivalent plan dimension to the vehicle that was struck. Although ice also fell around and outside the limits of the truck, we can assume that the entire footprint area of the vehicle was impacted by falling ice. Based on vertical compression estimates indicated above, it is our opinion that this specific icefall event resulted in a vehicle impact force of between 175 and 225 kips with an impact energy (KE) of between 1,300 and 1,400 kJ.

TABLE 4
Estimate of Vehicle Impact Energy & Force

			Fi = KE/S	
KINETIC ENERGY		**STOP DIST.**	**IMPACT FORCE**	
KE (KJ)	**KE (FT-LBS)**	**S or δ (FT)**	**Fi (LBS)**	**Fi (KIPS)**
1,361	1,003,990	1	1003990	1004
		2	501995	502
		3	334663	335
		4	250998	251
		5	200798	201
		6	167332	167
		7	143427	143

To put the results in context, the KE associated with a standard automobile moving 60 mph is approx. 500 kJ, so this icefall impact event was certainly significant and on-par with what we typically see with a large rockfall event. Given the magnitude of this icefall, and the frequency of ice recurrence at this site, the results were used to develop some of the mitigation strategies presented below.

Mitigation Options

Given the site's icefall history, high traffic volume, low catchment capacity and high slopes, MP 113.1 to MP 113.3 has a high risk for direct impacts to the roadway. As such, we recommend the following measures for mitigation of the icefall impacts at the site:

1. Installation on Remote Active Onsite Monitoring – Although monitoring is not a specific mitigation method per se, it would allow the DOT&PF to observe the site and record conditions real-time. We recommend that a weather station, slope sensor and camera type system (like RWIS) be installed adjacent to the slope so that ice development and behavior can be monitored. The data should be capable of being remotely-transmitted to DOT&PF decision makers so that further short- or long-term mitigation measures can be taken. The rock slope surface adjacent to the site's ice development location should be instrumented with a pyranometer to measure incoming solar radiation and a temperature gauge to measure rock slope surface temperatures within 2 to 4 in. of the slope surface.

2. Icefall Mitigation Measures – We recommend the consideration of following icefall mitigation measures throughout the effected interval:

   A. Slope Excavation (Solution No. 1) – Consider cutting the slope back by a minimum of 25 ft. This would allow for additional ditch catchment width adjacent to the shoulder and would provide additional horizontal offset between the slope and the travelled roadway. The rock slope cut angle (and ditch width) would require design for rockfall and global rock slope stability, in addition to icefall. The min. width indicated herein is preliminary and should be should be evaluated further during final design. The slope would need to be advanced using methods of controlled blasting, including provisions for perimeter control. Note that there could be ROW/easement restrictions at the above the slope, which must also be considered. This solution could be implemented in conjunction with the drainage solution described below for maximum effect.

B. Provide Upslope Drainage Diversion (Solution No. 2) – This is an ideal long-term solution and would facilitate diversion of upslope drainage water (including meltwater) such that persistent upslope sources of surface water are not captured by the slope crest, which is what is primarily responsible for ice slab development. Diversion of drainage water will also help to reduce local incidence of rockfall. In concept, drainage could be diverted northerly to where the slope face diverges away from the roadway; however, the hydraulics of this approach must be verified first. Any prospective alignment may require advancement of shallow borings to verify overburden thickness, bedrock depth and rock mass quality. This solution must consider ROW issues, permitting or construction access concerns.

C. Traffic Pattern Alteration (Solution No. 3) – We recommend that DOT&PF consider use of a modified traffic pattern that provides additional distance for potential failure of large ice slabs. In advance of a long-term (permanent) solution(s), this pattern could be transitioned to semi-permanent (e.g. weeks) based on M&O logistical requirements, projected weather and monitoring of slab behavior:

i. Proposed Traffic Diversion Plan & Detour for Large-Scale Ice Slabs: This pattern would mitigate direct impacts of large-scale, relatively thick, well developed ice formations that constitute near-continuous vertical slabs covering large portions of the slope face. This proposed pattern is intended to account for the additional outward rotational component of slab failure due to interaction of ice blocks as they fall to the ground. One lane (northbound) will not be sufficient to account for this effect, so we recommend that traffic be diverted further away from the slope and into the turn-out area. This pattern will require use of an additional lane (southbound lane) through the effected interval, resulting in a lane shift of approx. 24 ft. (two lanes) and use of the existing turn-out width. The lane shift should be per the Manual of Uniform Traffic Control Devices (MUTCD).

The pattern is not expected to mitigate the full effects of icefall shatter which could be cast across the roadway into the turn-out area; however, the pattern is expected to mitigate direct impact hazards. Shatter could be mitigated further through use of Jersey barrier type features (or similar); and/or, digging out the existing ditch to provide for additional depth to minimize "roll-out" of ice fragments (considering max. depth to prevent vehicle entry and roadside drainage hydraulics).

The timing for implementation of the traffic diversion should include immediate deployment of the diversion pattern when any of the following criteria are met:

- Any evidence of icefall fragments beyond limits of the catchment ditch;
- Measured rock surface temperatures greater than 32 deg. F;
- Observed active melting of ice on the rock slope, including evidence of wet or dripping ice slab or rock slope surfaces.

3. Alternative Mitigation Measures – These methods shown below could be adapted at the site; however, they present some logistical challenges and are not used routinely as icefall mitigation measures, both of which are described in Sec. 8.6:

    A. Install Pre-Hung Drapery – This "ice drape" option is in concept a highly effective option, applicable to almost all field conditions. In this specific location, we recommend use of high strength mesh material (e.g. G65/4 Tecco Mesh by GeoBrugg©) be used given its very high strength and relatively low weight. Wire rope anchorage points would be installed at the top of the slope in order to support the weight of the netting and assumed ice loads. Lower anchorage points and boundary cables would also be installed in order to prevent ice debris from exiting the drape and entering the roadway. The ice debris drape would be deployed (i.e. suspended over the rock-ice slope) once ice was suspected of being subject to instability based on observed field conditions such as slope warming or evidence of active sloughing. The drape would likely be between 150 and 200 ft. in length. There would likely be an aesthetic impact to the area although this would be a short-term impact as the drape would be drawn upward in the spring. Costs for the drape would be on the order of \$12 - \$18 per sq. ft. plus anchors, which would be in the range of \$150 per lin. ft. (assume 12 to 15 anchors at 10 ft. deep ea.). The system would require design by a geotechnical professional experienced with rock slope engineering.

    B. "Reinforced" Ice – Consists of installation of bars nearly perpendicular to the slope face in order to provide shear resistance along the ice-rock interface. The bars would need to be designed to resist shear and bending forces imparted by the ice, including minimum embedment. Additionally, the bars would need to be designed for maximum probable ice thickness at a given location. For initial conceptual cost estimating purposes, assume one bar every 6 to 10 ft. (pattern) embedded 5 ft. into rock. Installation costs can be assumed to be approx. \$150 per lin. ft. of embedment. The system would require design by a geotechnical professional experienced with rock slope engineering.

9.6 MP 74.1 to 74.9 SB Seward Highway

Site Observations

This stretch of the Seward Highway serves as a scenic entrance to south-central Alaska's Kenai Peninsula. The roadway is characterized as a relatively straight segment with two vertical curves as the grade increases to the south. The roadway consists of two southbound lanes and one northbound lane. There are two scenic turnouts on the northbound (east) side of roadway.

The southbound rock slopes between approx. MP 74.1 and 74.9 generally range between approx. 15 and 75 ft. in height, with south-southeast facing slope angles varying between 55 deg. (1.5V:1H) and nearly vertical. Observed roadside rockfall catchment ditch widths vary between 17 and 27 ft. depending on location along the roadway. Measured ditch depths ranged between 2 and 4 ft. Upslope surface water flow from snow melt and rain appears to be intercepted by the existing slope face, which results in fracture-controlled drainage and direct overflow at the slope crest. Slope crest interception of upslope water in visible in the vicinity of MP 74.0 and 74.8.

Figure 26 *– Ice slab conditions adjacent to MP 74.8 SB along Seward Highway (Photo by Scarptec, Inc.)*

During our 17 March 2017 visit, we observed the presence of three well-developed ice slabs at approx. MP 74.8, one of which appeared to be a "frozen waterfall" type feature (Fig. 4). The dimensions of these ice slabs are indicated in Appendix 2. Based on DOT&PF accounts, this ice feature is frequently observed during the winter season. This frozen waterfall feature was the largest of the three ice areas, encompassing a size of approx. 27 ft. in height by 22 ft. in slope parallel width by between 1 and 9 ft. in thickness. The ice slab thickness of up to 9 ft. points to consistent water seepage and steady outward slab growth. Ice was observed locally on other portions of this slope face; however, these areas of ice were small and localized. Photos of the three primary ice slabs is included above as Fig. 26.

Based on our site observations, the section of roadway between MP 74.1 and 74.9 can be characterized by its relatively low slope heights and wide catchment ditches. In addition, sight distances approaching 1,150 ft. are significant enough for most motorists to observe objects in the roadway. Large localized slabs of ice are capable of forming given persistent upslope flow of surface water sources; however, no known or documented icefall events have been recorded along this stretch of highway.

Technical Evaluations

MP 74.1 to 74.9 SB along the Seward Highway was found to have a "Low" preliminary icefall risk ranking based on Table 2. Ice has been known to develop within this interval, especially in the vicinity of MP 74.8. Based on the geometric analyses shown in Appendix 5, the catchment width available for ice slab wasting at the critical section (MP 74.8) is approx. 69% of the slope height. This is significant because falling slabs of ice are likely to be maintained by the ditch. Impact shatter events could periodically enter the roadway when icefall does occur; however, the 1,150 ft. of available sight distance for motorists will reduce chances of vehicle strikes with fallen ice in the roadway. Ice slab failure mechanisms within this interval are expected to be initial sliding or falling events, followed by slab crushing and subsequent shatter upon impact. There are no documented icefall events at this site based on the information we have to-date.

Mitigation Options

Based on our site observations, geometric evaluations and the relatively low risk of icefall impact shown in Table 2, we recommend that this site be subject to periodic monitoring controls as described in Sec. 9.12 below.

9.7 MP 57.9 to 58.2 NB Seward Highway

Site Observations

This northeast facing segment of slope consists of 15 to 120 ft. high cut rock slope that is convex inward in overall shape due to horizontal curvature of the two-lane roadway. The cut appears to have been advanced in three main lifts using drill and blast perimeter control methods, which resulted in the presence of two intermediate slope breaks (i.e. short benches). The slope angle appears to be approx. 70 deg. overall, with individual lifts likely cut at closer to 76 deg. (4V:1H). Catchment ditch widths vary between 19 and 26 ft. and ditch depths were observed to be 3 to 3.5 ft.

Figure 27 *– Ice slab conditions near MP 57.9 NB along Seward Highway (Photo by Scarptec, Inc.)*

While onsite, we made note of four discrete areas of developed ice on the slope. The approx. dimensions of these four areas is shown in Appendix 2. Most of the ice observed on 18 March 2017 appeared to be on the southern extents of the cut, and one specific area of well-developed ice was found at approx. MP 57.9, as shown in Fig. 27. The ice at MP 57.9 was just south of the main cut slope observed on 17 September 2016 and measured approx. 63 ft. wide by 28 ft. high by 5 to 12 ft. thick, and appeared to be generated from consistent upslope sources of water based on formation attributes. Similarly to the ice observed at MP 57.9, the other three areas of ice appeared to be formed due to steady consistent sources of upslope meltwater being intercepted by the slope crest.

The only area of developed ice on the main cut slope face was observed within a high angle discontinuity as reflected on Fig. 28. It is our opinion that this feature drains water from beyond and up-gradient of the slope and that the water freezes once seepage encounters the slope face; however, the ice within this fracture feature was highly localized and on the order of 1 to 4 ft. wide by 2 to 4 ft. in thickness.

Figure 28 *– Minor ice in fracture near MP 58.1 NB along Seward Highway (Photo by Scarptec, Inc.)*

Based on our site observations, ice formation appears to be driven primarily by melting of upslope snow pack and subsequent refreezing on the slope. Given the local topographic high (i.e. drainage divide) at the crest of the main cut slope, water appears to be drained preferentially toward the north and south ends of the main cut slope. Although ditches appear to possess adequate widths and significant ice development is most probable on the slope ends, the available horizontal sight distance is minimized at approx. 850 ft. due to curvature of the roadway. Additionally, the small segment of slope at approx. MP 57.9 has the conditions available to locally produce significantly thick slabs of ice, possibly approaching the edge of the road shoulder during active ice years; however, no known or documented icefall events have been recorded along this stretch of highway.

Technical Evaluations

MP 57.9 to 58.2 NB along the Seward Highway was found to have a "Low" preliminary risk ranking as shown on Table 2. Based on information provided by DOT&PF M&O staff, ice has been known to develop within this interval, but there have been no documented icefall impacts to the roadway based on the information we have collected. The area we observed well-developed ice in March 2017 was between MP 57.9 and 58.0, not on the much higher main slope between MP 58.0 and 58.2. We completed a geometric evaluation of the slope as shown in Appendix 5. The catchment width in the critical section (MP 57.9) is approx. 61% of the slope height and is generally expected to be sufficient for containing falling ice fragments; however, secondary impact shatter events could periodically enter the roadway when icefall does occur. The slightly reduced sight distance of 850 ft. would result in approx. 8 sec. of travel time before a vehicle struck ice debris in the roadway. Based on the observed slope angles, ice slab failure mechanisms within this interval are expected to be initial sliding or falling events, followed by slab crushing and subsequent shatter upon impact.

Mitigation Options

Based on our site observations, geometric evaluations and the relatively low risk of icefall impact, we recommend that this site be subject to periodic monitoring controls as described in Sec. 9.12 below.

9.8 MP 51.9 to 52.3 SB Seward Highway

Site Observations

The east-southeast facing slope segment between MP 51.9 and 52.3 represented the southern-most icefall study area along the Seward Highway. Existing rock slope heights along the southbound lane generally ranged between 11 and 30 ft. with slope angles between 75 and 80 deg. (approx. 4V:1H). Catchment ditch width varies between 23 and 24 ft. depending on location, which is significantly large with respect to the slope height. Ditch depths were measured and found to be approx. 3 ft. down to the ditch invert elevation. Southbound sight distances are on the order of approx. 4,000 ft. which is adequate for most motorists to see debris within the roadway.

Although exposed for viewing on 20 March 2017, much of the slope had snow cover and the ditches were filled with 2 to 3 ft. of hard crusty snow. While onsite we observed two specific areas of well-developed ice within this interval, both which appear to have developed from re-freezing of upslope melt water. The ice at approx. MP 52.0 was measured as 16 to 20 ft. in height by 100 ft. wide by 1 to 4 ft. thick. The ice slab observed at approx. MP 52.25 southbound was roughly trapezoidal in shape, mimicking the exposed slope face geometry, and measured approx. 8 to 22 ft. high by 62 ft. wide by 1 to 4 ft. thick as reflected in Fig. 29. Attributes of both ice slabs are further described in Appendix 2.

Also of significance at this specific location are the site's back-slope areas, which contain partially vegetated overburden slopes ranging between 32 deg. (2H:1V) and 45 deg. (1H:1V). These slopes appeared to have between 1 and 2 ft. of snowpack, much of which appeared subject to some degree of snow metamorphosis. In years with sufficient snowpack, it is likely that this snow transitions to ice by late winter/early spring.


03.20.2017 10:58

Figure 29 – *Ice development near MP 52.3 SB along Seward Highway (Photo by Scarptec, Inc.)*

Periodic icefall events have been documented by DOT&PF Silver Tip M&O staff to have entered the roadway section on two occasions, as described above in Sec. 9.2. The exact timing and locations of these events is unknown but based on the occurrence of these two events, ice could again enter the roadway; however, we again note the significance of the southbound sight distance and wide catchment ditches which appears adequate for icefall events emanating from the main slope face. Based on our observations of slope geometry and ice development in the field, it is our opinion that both events where ice impacted the roadway were the result of upslope ice sliding events, originating from back-slope areas above the slope crest.

<u>Technical Evaluations</u>

The ***MP 51.9 to 52.3 site was classified as having a "Low to Moderate" risk ranking*** as shown on Table 2. The reason for the slightly elevated ranking was due to the site's icefall history, with two documented icefall events as further described in Sec. 9.2. Based on our geometric evaluation as shown in Appendix 5, existing catchment width (100% of slope height) and road centerline offset (52 ft.) from the slope toe appear more than adequate enough to retain icefall events originating from the main slope face; however, the mere presence of "Beluga"-sized ice blocks within the roadway indicates that there may be alternate source zones outside the main rock slope limits. It is certainly possible that sliding ice slabs are being generated from the 1H:1V to 2H:1V back-slope area above the slope crest, although we have no way to corroborate this without further information on ice block size and travel distance(s).

<u>Mitigation Options</u>

Although the site was ranked as having a relatively low impact risk to the highway, we recommend that DOT&PF install active onsite monitoring in order to observe for signs of large ice blocks entering the roadway:

1. <u>Installation on Remote Active Onsite Monitoring</u> – Although monitoring is not a specific mitigation method, it would allow the DOT&PF to observe the site and record conditions real-time. We recommend that a weather station, slope sensor and camera type system (like RWIS) be installed adjacent to the slope so that ice development and behavior can be monitored. The data should be capable of being remotely-transmitted to DOT&PF decision makers so that further short- or long-term mitigation measures can be taken. The rock slope surface adjacent to the site's ice development location should be instrumented with a pyranometer to measure incoming solar

radiation and a temperature gauge to measure rock slope surface temperatures within 2 to 4 in. of the slope surface.
2. We also recommend that this site be subject to periodic monitoring controls as described in Sec. 9.12 below.

9.9 MP 38.3 to 38.5 SB Richardson Highway

Site Observations

We visited the site on 16 September 2016 and 14 March 2017 to observe late summer and late winter slope conditions, respectively. This segment of highway consists of a south-southwest facing rock slope with total heights ranging between approx. 20 and 73 ft. and slope angles of approx. 65 to 72 deg. An approx. 440-ft. long upper bench feature appears to exist at the northern half of the slope. Available rockfall catchment was measured as a consistent 31 ft. in width, with ditch depths between 4 and 4.5 ft.

Figure 30 *– Well-developed ice slab near MP 38.3 SB along Richardson Highway (Photo by Scarptec, Inc.)*

While onsite in September 2016, we observed running water at the southern end of this interval, which coincides with approx. MP 38.3, as shown in Fig. 30. This southern portion of the slope was generally wet, and based on the topography above the slope crest, there is ample drainage area available for surface water migration.

MP 38.3 is also a location that presented with significant ice development in March of 2017. There were at total of four areas of ice slab development observed, the most impressive of which was a frozen waterfall feature with a light blue aquamarine color measuring 29 ft. high by 33 ft. wide by up to 7 ft. in thickness. We also observed spotty areas of ice development but these were very small and would be handled by the existing ditch geometry. Additional details on each of the four main ice slab areas are included within Appendix 2.

Based on accounts from DOT&PF Valdez District M&O staff, the ice formation thickness can build-out extensively along this section of roadway; however, no known icefall events impacting the roadway have been recorded to-date. Due to the abundance of upslope water sources, this segment of slope could generate ice formation thicknesses that build-out toward the roadway, possibly temporarily reducing the available rockfall catchment area. Based on our field observations, it is our opinion that the wide catchment area, southbound sight distances on the order of 2,000 ft., low recorded icefall frequency, and relatively low AADT, will reduce the likelihood of significant impacts from icefall hazards.

Technical Evaluations

The ***MP 38.3 to 38.5 site was classified as having a "Low" risk ranking*** as shown on Table 2 due to the site's extensive minimum sight distance of approx. 2,000 ft., low traffic volume and relatively wide catchment area of 31 ft. Based on the geometric evaluation shown in Appendix 5, this catchment area represents 43% to 155% of the total observed slope height. The "critical section" where we observed the most significant ice development was at the south end of the cut near approx. MP 38.3 where catchment ditch width is approx. identical to slope height. The roadway centerline is approx. 49 ft. from the slope toe, which helps to establish horizontal offset from the observed ice slabs. Based on the observed slope angles, ice slab failure mechanisms within this interval are expected to be initial sliding or falling events, followed by slab crushing and subsequent shatter upon impact. Secondary impact shatter events could periodically enter the roadway when icefall does occur.

<u>Mitigation Options</u>

Based on our site observations, geometric evaluations and the relatively low risk of icefall impact shown in Table 2, we recommend that this site be subject to periodic monitoring controls as described in Sec. 9.12 below.

9.10 MP 22.7 to 23.3 SB Richardson Highway

<u>Site Observations</u>

The MP 22.7 to 23.3 segment of highway consists of a three lane section (one southbound lane down-grade and two uphill northbound lanes) of roadway through Thompson Pass toward the City of Valdez. We visited this site on 15 September 2016 and 16 March 2017 to observe late summer and winter slope conditions, respectively. Existing slope heights measured between 35 and 50 ft., and south-southeast facing slope angles were found to range between 70 and 85 deg. Rockfall catchment ditch widths were found to be significant in size, and measured between 35 and 40 ft. in horizontal width by 5 to 6 ft. in depth. Data collected during the September 2016 visit is included as Appendix 1.

Figure 31 *– Ice development near MP 22.9 SB along Richardson Highway (Photo by Scarptec, Inc.)*

While onsite in March 2017, we observed five areas of ice development, as shown in Fig. Nos. 31 and 32. These generally correlated with areas of water flow observed during our September 2016 visit, which appears to be from consistent sources of water above the main rock slope face. Ice formational features observed in the field confirm that the consistent addition and freezing of intercepted upslope surface drainage water results in growth of the ice slabs. Recorded data on the attributes of all five ice development areas are included in Appendix 2.

Based on accounts from DOT&PF Valdez District M&O staff, the ice formation thickness can build-out extensively along this section of roadway and icefall shatter fragments have been cast as far as the white painted shoulder fog line (approx. 41 to 46 ft. from slope toe) in previous years; however, no large fragments are known to have impacted the highway, as further described in Sec. 9.2.

Figure 32 *– Ice development near MP 23 SB along Richardson Highway (Photo by Scarptec, Inc.)*

Based on our field observations, we expect that the icefall hazard through the subject section of highway will be minimized by the extensive catchment ditch width, high sight distances of as much as 2,600 ft., low AADT and low frequency of icefall impacts to the roadway.

<u>Technical Evaluations</u>

The ***MP 22.7 to 23.3 site was classified as having a "Low" risk ranking*** as shown on Table 2 due to the site's extensive sight distance, low traffic volume and wide catchment area. Based on the geometric evaluation shown in Appendix 5, available existing catchment width varies between 70% and 100% of the slope height, which is generally sufficient enough to contain icefall direct impact events. The roadway centerline is between 49 and 54 ft. from the slope toe; however, this site does have a history of secondary impact shatter being cast horizontally out as far as the fog line. Based on the observed slope angles, ice slab failure mechanisms within this interval are expected to be initial sliding events, followed by slab crushing and subsequent shatter upon impact. Secondary impact shatter events could continue to periodically enter the roadway when icefall does occur.

<u>Mitigation Options</u>

Based on our site observations, geometric evaluations and the relatively low risk of icefall impact shown in Table 2, we recommend that this site be subject to periodic monitoring controls as described in Sec. 9.12 below.

9.11 MP 13.7 to 14.0 SB Richardson Highway

<u>Site Observations</u>

Figure 33 *– Limited ice development near MP 13.9 SB along Richardson Highway on 15 March 2017 (Photo by Scarptec, Inc.)*

This section of highway represents the southern-most site along the Richardson Highway, and is part of Keystone Canyon as the roadway snakes its way through the mountain pass and into the City of Valdez. The two lane highway is bounded by a rock slope on the southbound side and by the Lowe River along the northbound side. We visited this site on 15 September 2016 and 14 to 15 March 2017 to collect information on slope conditions during winter and summer months. The existing east-northeast facing slope from MP 13.7 to 14.0 southbound is irregular and stair-stepped along its profile, with localized bedrock overhangs. Slope height appeared to range between approx. 102 and 189 ft., with highly irregular overall slope angles estimated to be between 50 deg. and near-vertical depending on position along the highway. Measured rockfall catchment ditch width varied between 14 and 22 ft., with ditch depths of 3 to 5.5 ft.

In September of 2016, water flow was observed as both fracture-controlled seepage in "persistent" (i.e. long joint trace length) open discontinuities and also as surface water overflow from source areas above the main slope face. While onsite in March of 2017, we only observed small areas of ice development, as indicated in Fig. 33. Attributes of documented ice conditions at this site are included in Appendix 2. As described further in Sec. 9.2, icefall has been known to occur at this location, specifically in the area of MP 13.9, as demonstrated by a recent icefall event in December of 2017. The relatively consistent supply of upslope water sources and irregular slope profile can result in well-developed ice flows, which are frequented by the ice climbing community; however, we understand that the extent of ice development is highly variable from year-to-year based on precipitation and temperatures.

Given the site's history with direct icefall impacts to the roadway, limited site distances on the order of 600 ft., consistent upslope sources of water, minimal effective ditch widths, and highly irregular slope profile including overhangs, it can be expected that this site will continue to periodically produce slabs of falling ice and present a long-term winter and early spring hazard to those using the roadway.

Technical Evaluations

The ***MP 13.7 to 14.0 site was classified as having a "Moderate to High" risk ranking*** as shown on Table 2. Much like with MP 113 on the Seward Highway, we based the technical evaluations shown below on available icefall impact history, the most recent of which was on 13 December 2017 (Fig. 22). Given the highly irregular nature of this slope profile and our onsite discussions with DOT&PF M&O staff, it appears that ice frequents this specific location each year. Even though the slope is significantly higher than where the ice usually forms, we opted to use data from the December 2017 event to back-calculate event characteristics which were the used for development of mitigation options.

Geometric Analysis

The findings from the initial site screening are also reflected in the geometric analysis of the "critical section" which is at approx. MP 13.9. Measured ditch width was found to be 22 ft.; however, effective (i.e. the actual useful width) catchment width is locally reduced by upwards of 4 ft. given the overhung nature of the lower rock slope shelf where ice was developed. The catchment depth was measured as 5 ft., a portion of the direct impact field overlaps the southbound travel lane, as indicated in Appendix 5.

Based on the debris field limits and fragmentation, it appears that the slab initially lost its adhesion strength, fell and then impacted the ditch, resulting in a localized rotational failure. With a slab height of 20 ft. rotating outward toward the roadway, the impact limits would be directly at the shoulder of the roadway. Secondary impact shatter would be cast horizontally from the main impact. This is close to what we observed in the two photographs we witnessed.

Post-Failure Impact Energy

Based on photos provided by DOT&PF M&O staff, we estimated the ice block size that fell on 13 December 2017 to be approx. 20 ft. high by 8 ft. wide by 3 ft. thick. This results in a block volume of approx. 480 c.f. and a block weight of 27,500 lbs. Assuming that the fall distance is calculated from the block's center of mass at 10 ft. above the slope toe, the kinetic energy (KE) at impact is approx. 372 kJ. To look at this even more conservatively, given the additional slope height well above this section of failed ice, we could assume a fall height of the full 20 ft. at top of ice slab, which results in an impact energy of 745 kJ, as indicated in Appendix 7. Estimates of impact force are highly dependent upon assumed stopping (i.e. deceleration) distance and we do not have an impact event to compare; however, if a barrier was considered within this interval, design would require consideration of impact energies between 250 and 750 kJ.

Mitigation Options

Given the site's icefall history, relatively low catchment capacity and high slopes, MP 13.7 to 14.0 has a moderate to high level of risk for direct impacts to the roadway. We based the following recommendations on the location of known ice development observed at approx. MP 13.9. As such, we recommend the following measures for mitigation of icefall impacts during periods when ice is observed adhered to the slope:

1. Installation on Remote Active Onsite Monitoring – Although monitoring is not a specific mitigation method, it would allow the DOT&PF to observe the site and record conditions real-time. We recommend that a weather station, slope sensor and camera type system (like RWIS) be installed adjacent to the slope so that ice development and behavior can be monitored. The data should be capable of being remotely-transmitted to DOT&PF decision makers so that further short- or long-term mitigation measures can be taken. The rock slope surface adjacent to the site's ice development location should be instrumented with a pyranometer to measure incoming solar radiation and a temperature gauge to measure rock slope surface temperatures within 2 to 4 in. of the slope surface.

2. Short-Term Mitigation Measures – Would be used prior to enacting permanent icefall mitigation solutions or as-needed throughout the effected interval based on development of new ice slabs. Given the limited roadway width available for traffic pattern alterations and highly irregular nature of the slope morphology, short-term mitigation measures will be very challenging to implement and maintain at this site:

    A. Temp. Traffic Alterations: Given this width restriction, adjacent river, very high slope walls, and estimated direct impact distance, short-term measures may result in loss of the southbound lane for a distance of approx. 100 ft. through the effected interval (i.e. one lane shift). Two-way signage could be deployed well in advance of the lane shift or automated/manual flaggers would be required through the effected interval (e.g. 6H-10). We have assumed that longer-term use of traffic alterations (measured in weeks) is not practical for this location given the limited roadway section width.

Timing of implementation of traffic diversion to include immediate deployment of the diversion pattern when any of the following criteria are met:

- Any evidence of icefall fragments beyond limits of the ditch;
- Measured rock surface temperatures greater than 32 deg. F;
- Observed active melting of ice on the rock slope, including evidence of wet or dripping ice slab or rock slope surfaces.

In cases where immediate deployment is not possible and will take more than 4 to 6 hours, consider use of temporary cones/barrels to prohibit travel within the SB lane until a full traffic diversion is in-place.

3. Long-Term Icefall Mitigation Measures – We recommend DOT&PF consider the following permanent mitigation measures throughout the effected interval (Note: We only present those solutions that could reasonably be applied in this specific area. There are other highly effective options, like slope blasting and regrading; however, we have assumed these highly invasive methods would not be practical at this site):

   A. Installation of Icefall Barrier – This is truly an effective permanent solution, as the barrier would be installed once with minimal long-term maintenance. Given the limited roadside catchment geometry, the barrier would need to be “stiff” and relatively low deflection (closer to that of a “wall”). The rockfall barrier would likely be on the order of approx. 50 to 80 ft. in length, use embedded (drilled) or bolted (flange-connected) steel posts with high-strength rockfall netting suspended between each post. Critical design considerations would include maximum ice thickness (for horizontal slope-roadway offset) and barrier height. A rockfall barrier would be relatively expensive capital investment in the short term, but would require minimal long-term maintenance. Alternatively, a structural wall could be built along the interface of the shoulder and catchment ditch. One downside to this approach is the limited space available within the roadway section, which may require reduced speed limits or signage in advance of the barrier interval. This feature would need to be designed to consider max. ice thickness, lateral impact load(s) and foundation anchorage.

9.12 General Mitigation Recommendations

Detailed preliminary site-specific mitigation recommendations were provided for MP 113.1 to 113.3 along the Seward Highway and MP 13.7 to 14.0 along the Richardson Highway based on impact risk assessment. General recommendations relative to long-term monitoring should be applied to the remaining five sites that present relatively low icefall impact risks.

1. We recommend that DOT&PF consider general icefall hazard monitoring for the five sites with a “low” icefall impact risk rating. This can consist of simple M&O observation of significant ice development locations and specific icefall events (if they occur) in the course of normal duties.

Areas of significant ice development should be noted in daily or weekly log books, as would be standard for rockfall or landslides. Documented icefall events should be logged in MMS.

2. We recommend that DOT&PF require consideration of icefall hazards for future proposed rock slope excavation projects and proposed rock slope stabilization projects along existing rock cuts. Although icefall evaluation is still relatively new in its application, technical evaluations should consider presence of upslope water sources (including from melting of snowpack), loss of adhesive strength along ice-rock contacts, potential maximum ice slab dimensions, required catchment geometry and icefall retention capacity (in addition to that required for rockfall). ***Minimum catchment widths designed for rockfall may not be sufficient for icefall capture***, as ice can develop wherever upslope water is abundant. The values provided herein could be used for reference.

9.13 Risk Matrix Showing Mitigations

As a final element to this report, and in order to show the effect of the mitigation options on the icefall impact risk, we included recommended site-specific treatments within Appendix 8. This table presents Preliminary Icefall Impact Risk Matrix (PIIRM) results, only with inclusion of the mitigation options for MP 113.1 to 113.3 and MP 13.7 to 14.0, along the Seward and Richardson Highways, respectively. This tool will allow planners to consider the effect that mitigation techniques will have with respect to the unmitigated scenario.

TABLE 5
Effect of Mitigation on Prelim. Risk Ranking

MP 113.1 – MP113.3 SEW	
Unmitigated Risk Ranking	HIGH
Slope Excavation	LOW
Add Drainage Diversion	LOW
Add Prop. Traffic Pattern	LOW
Pre-Hung Drapery	LOW - MOD
Reinforced Ice	LOW - MOD
MP 13.7 – MP 14.0 RICH	
Unmitigated Risk Ranking	MOD-HIGH
Add Short-Term Traffic	LOW - MOD
Add Permanent Barrier	LOW

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APPENDIX NO. 1

Site Visit No. 1 Field Data

CLIENT NAME AND DIVISION:	Alaska DOT&PF/RESEARCH
PROJECT NAME:	PHASE 2 - SITE SPECIFIC ICEFALL HAZARD EVALUATION
HIGHWAY:	Seward
APPROX. MILEPOST NO.:	113.1-113.3
SIDE OF HIGHWAY:	Northbound
SITE INCL. IN USMP:	Yes
AS-BUILT RECORDS EXIST:	Yes

STAFF:	D. SCARPATO
DATE:	9/12/2016
WEATHER:	Breezy, Showers, 50s

SCARP TEC INC.
ROCK ENGINEERING SOLUTIONS

1. ROADWAY OBSERVATIONS:	
A. EFFECTIVE ROADWAY WIDTH (FT.)	90 ft. CLF@RR to toe slope; 12 ft lane widths
B. NUMBER OF LANES	2 lanes (n/s) + turnout & slow lane
C. EFFECTIVE SHOULDER WIDTH (FT.)	Paved @ 6ft northbound lane
D. PRESENCE OF HORIZ./VERT. CURVES	No VC; HC is not for >500ft N/S of slope
E. POSTED SPEED LIMIT (MPH)	55

2. SLOPE OBSERVATIONS	
A. EFFECTIVE ROADWAY LENGTH (FT.)	Approx. 950
B. SLOPE HEIGHT RANGE [MIN/MAX/AV] (FT.)	50 - 140; 80 - 100 typ.for rock slope
C. SLOPE PROFILE IN PLAN & SECTION	Linear/stepped/planar
D. PRESENCE OF BACKSLOPE	Yes
E. SLOPE MATERIAL:	Rock (shallow overburden on backslope)
F. SLOPE ANGLE RANGE (MIN/MAX/AV)	86° overall (max); 70°-88° typ.
G. PRESENCE & TYPES OF VEGETATION	Numerous saplings and grass @ ledges and joints
H. SLOPE ASPECT & DIP DIRECTION	Dip Az.190°; S/SW facing slope (207 deg. Az. corrected)
I. PRESENCE OF INT. SEEPAGE & SOURCE	Yes - major joints show seepage
J. PRESENCE OF SURFACE WATER & SOURCE	Moist soils; 2-3 small channels
K. EVIDENCE OF SLOPE INSTABILITY & TYPE(S)	Periodic rockfall here

3. BEDROCK OBSERVATIONS	
A. ROCK LITHOLOGY/TYPE/UNIT	K - sed; seafloor rocks (ophiolites); melange
B. ROCK COLOR	Light gray and dark gray; brown Ox staining
C. FIELD EST. COMP. STRENGTH (PSI)	R3-R4
D. WEATHERING/ALT. INDEX	W1-W3; Hi.localized W4 along some open joints
E. CRYSTALLINE TEXTURE OR FABRIC	Sheared
F. NO. OF DISCONTINUITY SETS	Fabric makes diff. to tell but at least 5 sets
G. DISCONTINUITY SET ORIENTATIONS	Undulating/irregular
H. EST. JOINT APERTURE (IN.)	Tight to as wide as 12" in persistent joints
I. EVIDENCE OF JOINT SEEPAGE	Yes; see above. Not consistent across slope
J. PRESENCE & TYPE JOINT INFILLING SOILS	Locally in persistent joints; sand/silt/crushed rock
K. EVIDENCE OF ROOT JACKING	No, not big enough trees near crest
L. VEGETATION IN/ON JOINTS	Yes - on benches/shelves
M. ROCK SURFACE ROUGHNESS - MICROSCALE	R - VR
N. ROCK SURFACE ROUGHNESS - MACRO (JRC)	Vertical section @ mod-hi JRC
O. GEOLOGIC STRUCTURE	Jointed; blocky & slabby

4. SOIL OBSERVATIONS	Org	Org/colluvium	
A. SOIL TYPE & CLASS.	Till	Till	Till is SM + gravel; Silt appears v. stiff
B. OVERBURDEN THICKNESS (FT.)	Approx. 0' - 10' ±		

5. EVIDENCE OF ICE DEVELOPMENT	
A. STRIPPED VEGETATION OR SOIL	Areas of low growth only (<1ft) w/clusters of trees
B. CONTORTED TREE GROWTH	No
C. POLISHED/GROOVED ROCK SURFACES	Yes - but thought to be old glacial activity
D. OBS. ICE JACKING OF ROCK BLOCKS	No
E. SITE HISTORY OF ICE DEVELOP/ICEFALL	Yes; 6 April 2012 icefall event; ice climbing site *Icefall event 2012 @ ~mp 113.25

6. ROCKFALL CATCHMENT		
A. EFFECTIVE DITCH WIDTH (FT.)	8' - 14' (laser range finder)	
B. EFFECTIVE DITCH HEIGHT (FT.)	3'	
C. EXISTING DITCH CONDITION	PARTLY FILLED	10%
D. OBS. DAMAGE TO ROADWAY	No	
E. SITE HISTORY OF ROCKFALL	Yes	

7. GENERAL COMMENTS ON SITE

- Presence of blasted benches @ 3-6ft wide; steeply sloping bench heels. Likely act as "keys" and help hold ice.
- Rough/irregular slope surface likely helps ice adhesion.
- Above MP113.252012 icefall event, found 2-3 meandering culches for periodic water flow. Very wet but not flowing today even after very rainy last few days and very rainy August. Channels approx. 3'-5'W x 1'-3'D. See photos.

Veg - Trees: mostly cottonwoods, some conifers
Low growth: Devils club, blueberry

SCARP TEC Inc.
ROCK ENGINEERING SOLUTIONS

CLIENT NAME AND DIVISION:	Alaska DOT&PF/RESEARCH
PROJECT NAME:	PHASE 2 - SITE SPECIFIC ICEFALL HAZARD EVALUATION
HIGHWAY:	Richardson Highway
MILEPOST/MILEPOINT NO.:	13.7-14.0 *Keystone Canyon area
SIDE OF HIGHWAY:	Southbound
AS-BUILT RECORDS EXIST:	YES

STAFF:	D. SCARPATO
DATE:	9/14-9/15/16
WEATHER:	Rainy, Cool <50's calm wind both days

1. ROADWAY OBSERVATIONS:

A. EFFECTIVE ROADWAY WIDTH (FT.)	32 ft. total; 12 ft lanes
B. NUMBER OF LANES	2
C. EFFECTIVE SHOULDER WIDTH (FT.)	4 ft. paved ea. side + 2-3 ft. agg. base, then ditch
D. PRESENCE OF HORIZ./VERT. CURVES	HC = yes; VC = no, but downhill through section
E. POSTED SPEED LIMIT (MPH)	55
	N/E bound lane has river ditch

2. SLOPE OBSERVATIONS

A. EFFECTIVE ROADWAY LENGTH (FT.)	Approx. 1,300 (lasered)
B. SLOPE HEIGHT RANGE [MIN/MAX/AV] (FT.)	102 - 189
C. SLOPE PROFILE IN PLAN & SECTION	Planar and stepped
D. PRESENCE OF BACKSLOPE	Cannot see; Too high above if present
E. SLOPE MATERIAL:	ROCK
F. SLOPE ANGLE RANGE (MIN/MAX/AV)	Hi.variable. As low as 50° to vertical/overhung
G. PRESENCE & TYPES OF VEGETATION	Small saplings/grass/moss; conifers @ top slope
H. SLOPE ASPECT & DIP DIRECTION	Gen. E/NE @ 063 - 075
I. PRESENCE OF INT. SEEPAGE & SOURCE	Joint seepage observed in persistent joints
J. PRESENCE OF SURFACE WATER & SOURCE	Yes; abundant - stream @ north end + "car wash rock" waterfall
K. EVIDENCE OF SLOPE INSTABILITY & TYPE(S)	Occasional rockfall; observed debris from two small rock failures.

3. BEDROCK OBSERVATIONS

A. ROCK LITHOLOGY/TYPE/UNIT	Late K sed. Rocks of Valdez group; turbidites - low grade meta onset
B. ROCK COLOR	Brown and dark to light gray
C. FIELD EST. COMP. STRENGTH (PSI)	R4 - R5
D. WEATHERING/ALT. INDEX	W1 - W3; Most W2
E. CRYSTALLINE TEXTURE OR FABRIC	Laminated/slatey cleavage; stylolites
F. NO. OF DISCONTINUITY SETS	4 primary
G. DISCONTINUITY SET ORIENTATIONS	See notes
H. EST. JOINT APERTURE (IN.)	Up to 36" @ car wash; tight to 6" for other persistant joints
I. EVIDENCE OF JOINT SEEPAGE	Yes, in persistant joints
J. PRESENCE & TYPE JOINT INFILLING SOILS	Minor/localized
K. EVIDENCE OF ROOT JACKING	Not observed
L. VEGETATION IN/ON JOINTS	At top, yes; not obvious on main slope
M. ROCK SURFACE ROUGHNESS - MICROSCALE	See notes
N. ROCK SURFACE ROUGHNESS - MACRO (JRC)	Hi. Variable
O. GEOLOGIC STRUCTURE	Massive/bedded; slabby; slatey in places.
P. ICEFALL CONTROL SURFACES	J1, J2 @ car wash; or "main slope face". See notes

4. SOIL OBSERVATIONS

A. SOIL TYPE & CLASS.	Not observed	Not on main slope face; could not safely access top/backside
B. OVERBURDEN THICKNESS (FT.)	Not observed	

5. EVIDENCE OF ICE DEVELOPMENT

A. STRIPPED VEGETATION OR SOIL	Clean surfaces @ car wash rock; local moss or grass
B. CONTORTED TREE GROWTH	A few bent large saplings and trunks
C. POLISHED/GROOVED ROCK SURFACES	No
D. OBS. ICE JACKING OF ROCK BLOCKS	No
E. SITE HISTORY OF ICE DEVELOP/ICEFALL	Ice develops each year @ "car wash rock" and other wet locations at this site.

6. ROCKFALL CATCHMENT

A. EFFECTIVE DITCH WIDTH (FT.)	Range 14' -21'
B. EFFECTIVE DITCH HEIGHT (FT.)	Range 3' - 5.5'
C. EXISTING DITCH CONDITION	PARTLY FILLED 5-10% max %
D. OBS. DAMAGE TO ROADWAY	Minor dings below Car Wash Rock
E. SITE HISTORY OF ROCKFALL	Occasional, not frequent. Two small block slides

7. GENERAL COMMENTS ON SITE

1. Completed a "drive-by" w/Robert Dunning of M&O on 9/14/16. See field notes.
2. Ditch dim. @ "car wash rock" = 22'W x 5'D (max).
3. Slope height @ "car wash rock" = ~112ft.
4. Slope profile @ "car wash rock: = stepped.
5. Previous rock slope failures appear strongly struc.controlled; prim.rockfalls from sliding or toppling.
6. Discontinuities @ 2 major wet/flowing areas: #1 "CAR WASH ROCK"
    - J1 = 076/39; R, PL
    - J2 = 247/71; wobbles in direction; R-SM, PL
    - J3 = 340/67 (BEDDING); R-SM; PL
    - J4 = 119/53; R-SM, PL

#2 "MAIN SLOPE FACE" @ 064/82 (VR-R, PL); wavy surf.
100° west/south of car wash

CLIENT NAME AND DIVISION:	Alaska DOT&PF/RESEARCH
PROJECT NAME:	PHASE 2 - SITE SPECIFIC ICEFALL HAZARD EVALUATION
HIGHWAY:	Richardson
MILEPOST/MILEPOINT NO.:	22.7-23.3 ± Thompson Pass area
SIDE OF HIGHWAY:	Southbound
AS-BUILT RECORDS EXIST:	YES

STAFF:	D. SCARPATO
DATE:	9/15/2016
WEATHER:	Rain, Wind <40s Been raining for a few days

1. ROADWAY OBSERVATIONS:	
A. EFFECTIVE ROADWAY WIDTH (FT.)	36 ft paved width; 10 ft south lane width
B. NUMBER OF LANES	3 (1 southbound, 2 northbound)
C. EFFECTIVE SHOULDER WIDTH (FT.)	6 ft, then into ditch
D. PRESENCE OF HORIZ./VERT. CURVES	No HC; no VC; consistant down grade
E. POSTED SPEED LIMIT (MPH)	65

2. SLOPE OBSERVATIONS	
A. EFFECTIVE ROADWAY LENGTH (FT.)	Approx. 2640
B. SLOPE HEIGHT RANGE [MIN/MAX/AV] (FT.)	35 to 50
C. SLOPE PROFILE IN PLAN & SECTION	Linear for both
D. PRESENCE OF BACKSLOPE	No, rel. flat top
E. SLOPE MATERIAL:	ROCK
F. SLOPE ANGLE RANGE (MIN/MAX/AV)	70° to 85°
G. PRESENCE & TYPES OF VEGETATION	Unknown type; all small saplings and brush
H. SLOPE ASPECT & DIP DIRECTION	AZ 149° (S/SE); roadway trend @ 239° AZ (166° aspect AZ. corrected)
I. PRESENCE OF INT. SEEPAGE & SOURCE	Minor; mostly surface
J. PRESENCE OF SURFACE WATER & SOURCE	Yes; 1 consistent flow @ 400ft south MP23, other moist areas
K. EVIDENCE OF SLOPE INSTABILITY & TYPE(S)	Minor rockfall and sloughing/raveling

3. BEDROCK OBSERVATIONS	
A. ROCK LITHOLOGY/TYPE/UNIT	Valdez group; late K sed. Rocks - turbidites. Low grade meta.applied
B. ROCK COLOR	Light grey w/rusting to rocks? Looks like muddy siltstone
C. FIELD EST. COMP. STRENGTH (PSI)	R2-R4
D. WEATHERING/ALT. INDEX	W2-W3
E. CRYSTALLINE TEXTURE OR FABRIC	Laminated/slately
F. NO. OF DISCONTINUITY SETS	2 obv.sets; J_1=bedding; J_2 = joint (less freq)
G. DISCONTINUITY SET ORIENTATIONS	J_1 @ 335° /22°; J_2 trace @~060°/80°
H. EST. JOINT APERTURE (IN.)	Bedding gen.tight to 1" unless loose rock
I. EVIDENCE OF JOINT SEEPAGE	Minor; mostly surface
J. PRESENCE & TYPE JOINT INFILLING SOILS	Minor; broken/weathered rock
K. EVIDENCE OF ROOT JACKING	No
L. VEGETATION IN/ON JOINTS	Yes, see 2G above
M. ROCK SURFACE ROUGHNESS - MICROSCALE	Rough to v.rough
N. ROCK SURFACE ROUGHNESS - MACRO (JRC)	Planar to stepped; >JCR
O. GEOLOGIC STRUCTURE	Thinly bedded, fissile and slatey up section; more massive downhill

4. SOIL OBSERVATIONS	
A. SOIL TYPE & CLASS.	NA
B. OVERBURDEN THICKNESS (FT.)	<1 ft, mostly rock

5. EVIDENCE OF ICE DEVELOPMENT	
A. STRIPPED VEGETATION OR SOIL	No
B. CONTORTED TREE GROWTH	Yes, some bent trunks in saplings; could also be partly from block creep
C. POLISHED/GROOVED ROCK SURFACES	No
D. OBS. ICE JACKING OF ROCK BLOCKS	No
E. SITE HISTORY OF ICE DEVELOP/ICEFALL	Yes, along areas w/active water flow; icefall has occurred here within ditch; Shatter on shoulder.

6. ROCKFALL CATCHMENT	
A. EFFECTIVE DITCH WIDTH (FT.)	35 to 40ft consistent
B. EFFECTIVE DITCH HEIGHT (FT.)	5 to 6 ft
C. EXISTING DITCH CONDITION	PARTLY FILLED <5 % not much debris
D. OBS. DAMAGE TO ROADWAY	No
E. SITE HISTORY OF ROCKFALL	Just small events contained in ditch

7. GENERAL COMMENTS ON SITE

1. Two turn-outs on northbound side
2. Robert Dunning said that the ice growth is more like large icicles that grow together fused.
3. Ice fragments from shatter have made it to shoulder.
4. Active water discharge @ 400 ft south of MP23; active ice develop and icefall. At this location, specifics incl:
   - Slope height @~ 47'
   - Slope angle @~ 80° (acts as interface ice-rock)
   - Ditch width = 35 ft; depth = 5 ft
5. Need to verify w/aerial photo but likely that water is flowing parallel to roadway above cut, then is partially diverted toward slope face.
6. Blasted slope, can see half-casts; HCF ~ 25-40%

*see also photo seq

Laser -

MP23: Southerly by 6 snow poles x 200ft/pole = 1200 ft //-(0.23mi) +(0.27 mi)

Northerly by 5 poles x 200ft/pole = 1000 ft; +416 ft pull-out = 1416 ft//

CLIENT NAME AND DIVISION:	Alaska DOT&PF/RESEARCH
PROJECT NAME:	PHASE 2 - SITE SPECIFIC ICEFALL HAZARD EVALUATION
HIGHWAY:	Richardson
MILEPOST/MILEPOINT NO.:	38.3-38.5 ±
SIDE OF HIGHWAY:	Southbound
AS-BUILT RECORDS EXIST:	YES

STAFF:	D. SCARPATO
DATE:	9/16/2016
WEATHER:	Overcast, Showers mid-40s calm winds

1. ROADWAY OBSERVATIONS:

A. EFFECTIVE ROADWAY WIDTH (FT.)	36' ft paved; 12' lane width
B. NUMBER OF LANES	2
C. EFFECTIVE SHOULDER WIDTH (FT.)	5' - 15' (incl compact soil west); 6 ft. paved west, 6 ft. east
D. PRESENCE OF HORIZ./VERT. CURVES	Yes; straightaway thru slope segment; bottom of small
E. POSTED SPEED LIMIT (MPH)	65 VC sight dist. not obstructed
	Sight dist > 1,000 ft in S/W bound lane (slope side) ~2,000 ft NB

2. SLOPE OBSERVATIONS

A. EFFECTIVE ROADWAY LENGTH (FT.)	Approx. 780
B. SLOPE HEIGHT RANGE [MIN/MAX/AV] (FT.)	63'-73'; 20' @ far west end (total height)
C. SLOPE PROFILE IN PLAN & SECTION	Linear/planar cut face
D. PRESENCE OF BACKSLOPE	Yes; long run. See notes
E. SLOPE MATERIAL:	ROCK
F. SLOPE ANGLE RANGE (MIN/MAX/AV)	65° to 70° overall; HC @ 70-72°
G. PRESENCE & TYPES OF VEGETATION	Trees & saplings @ top of cut & back slope
H. SLOPE ASPECT & DIP DIRECTION	175° AZ (road @085° trend); south facing (192 deg. Az. corrected)
I. PRESENCE OF INT. SEEPAGE & SOURCE	No, minimal if any
J. PRESENCE OF SURFACE WATER & SOURCE	Yes; small waterfall feature
K. EVIDENCE OF SLOPE INSTABILITY & TYPE(S)	Localized rockfall; 1' - 2' typ (infrequent)

3. BEDROCK OBSERVATIONS

A. ROCK LITHOLOGY/TYPE/UNIT	Late K Valdez group; turbidites? Sandy siltstone w/mud sim to	
B. ROCK COLOR	Light to dark grey w/rust staining graywacke	
C. FIELD EST. COMP. STRENGTH (PSI)	R3 to R5	
D. WEATHERING/ALT. INDEX	W2; local W3	
E. CRYSTALLINE TEXTURE OR FABRIC	Laminated; occ vugs	
F. NO. OF DISCONTINUITY SETS	3 primary (bedding + 2 ortho joints) + rand.	
G. DISCONTINUITY SET ORIENTATIONS	J_1 (bedding) = 163/68; J_2 = ST@350° vert.; J_3 = 327/40°	
H. EST. JOINT APERTURE (IN.)	Typ. 1" tight	
I. EVIDENCE OF JOINT SEEPAGE	No	
J. PRESENCE & TYPE JOINT INFILLING SOILS	NA	
K. EVIDENCE OF ROOT JACKING	No	
L. VEGETATION IN/ON JOINTS	Saplings, moss, grass; lots of moss on waterfall area ± 5ft E.W.	
M. ROCK SURFACE ROUGHNESS - MICROSCALE	R-VR; UN-W	
N. ROCK SURFACE ROUGHNESS - MACRO (JRC)	Wavy @ multiple scales; >JCR	
O. GEOLOGIC STRUCTURE	Bedded sed.rocks; massive; note that the fines laid down as part of the turbidite dep were dep on irregular, wavy surfaces.	Looks like crenulation cleavage; results in rough surface w/>JCR.

4. SOIL OBSERVATIONS

A. SOIL TYPE & CLASS.	NA
B. OVERBURDEN THICKNESS (FT.)	NA

5. EVIDENCE OF ICE DEVELOPMENT

A. STRIPPED VEGETATION OR SOIL	No
B. CONTORTED TREE GROWTH	Saplings/small trees at crest w/bent trunks
C. POLISHED/GROOVED ROCK SURFACES	No
D. OBS. ICE JACKING OF ROCK BLOCKS	No
E. SITE HISTORY OF ICE DEVELOP/ICEFALL	Yes; icicles fuse together acc.to Robert Dunning

6. ROCKFALL CATCHMENT

A. EFFECTIVE DITCH WIDTH (FT.)	31
B. EFFECTIVE DITCH HEIGHT (FT.)	4.0-4.5'
C. EXISTING DITCH CONDITION	PARTLY FILLED <5% not much at all
D. OBS. DAMAGE TO ROADWAY	No
E. SITE HISTORY OF ROCKFALL	No; v.small blocks obs.locally in ditch

7. GENERAL COMMENTS ON SITE

1. Note that J_1 bedding forms slope face in many cases.
2. At water flow area @~MP 38.3:
   - -Slope height = 34'
   - -Ditch width = 28'
   - -Ditch depth = 4'
3. Lots of slope face covered in tufa-like deposit where flowing water or v.wet conditions obs.
4. Culvert # 2185 @ south/west end site
5. HCF @ 75-80% except @ far north end where <25%
6. Upper bench exists for approx. 440 ft. from northern end
7. Backslope & water source: see sketch @ top of page.

Note: Ditch width in initil field notes included 3 ft of unpaved shoulder. Add this to ditch width.

CLIENT NAME AND DIVISION:	Alaska DOT&PF/RESEARCH	**STAFF:**	D. SCARPATO
PROJECT NAME:	PHASE 2 - SITE SPECIFIC ICEFALL HAZARD EVALUATION	**DATE:**	9/17/2016
HIGHWAY:	Seward	**WEATHER:**	P. Cloudy
MILEPOST/MILEPOINT NO.:	MP 51.9-52.3 (odometer)		mid 40s
SIDE OF HIGHWAY:	Southbound		calm winds
AS-BUILT RECORDS EXIST:	YES		

1. ROADWAY OBSERVATIONS:

A. EFFECTIVE ROADWAY WIDTH (FT.)	12 ft lane widths; 48 ft total
B. NUMBER OF LANES	3; 2 uphill south bound; 1 downhill northbound
C. EFFECTIVE SHOULDER WIDTH (FT.)	7 ft on south side (4' paved, 3ft agg.base)
D. PRESENCE OF HORIZ./VERT. CURVES	No HC; yes downhill on VC
E. POSTED SPEED LIMIT (MPH)	65 - but people drive 75-85

2. SLOPE OBSERVATIONS

A. EFFECTIVE ROADWAY LENGTH (FT.)	Approx. 980 (laser)
B. SLOPE HEIGHT RANGE [MIN/MAX/AV] (FT.)	11' to 30'
C. SLOPE PROFILE IN PLAN & SECTION	Linear & planar
D. PRESENCE OF BACKSLOPE	Yes but flat/low angle for long distance
E. SLOPE MATERIAL:	ROCK
F. SLOPE ANGLE RANGE (MIN/MAX/AV)	75° - 80° dipslope
G. PRESENCE & TYPES OF VEGETATION	Yes, saplings/moss/grass; conifers up high
H. SLOPE ASPECT & DIP DIRECTION	Road @ 350 AZ; slope @ 080 (east)
I. PRESENCE OF INT. SEEPAGE & SOURCE	No
J. PRESENCE OF SURFACE WATER & SOURCE	Yes @ 3 spots, running water. Lots of moist spots
K. EVIDENCE OF SLOPE INSTABILITY & TYPE(S)	Raveling from frost wedge cycles

3. BEDROCK OBSERVATIONS

A. ROCK LITHOLOGY/TYPE/UNIT	Late K sed.rocks (Valdez group); app.be slate + quartz strings
B. ROCK COLOR	Slate gray w/brown-tan rust covering locally
C. FIELD EST. COMP. STRENGTH (PSI)	R2-R3
D. WEATHERING/ALT. INDEX	W2 w/local W3
E. CRYSTALLINE TEXTURE OR FABRIC	Aphanitic; lam.w/slatey cleavage. Sheared text.in many locations
F. NO. OF DISCONTINUITY SETS	2 primary + lots of FX's some slicks obs.
G. DISCONTINUITY SET ORIENTATIONS	J_1 = 095/82 (bed/fol); J_2 = 193/76 (side joint)
H. EST. JOINT APERTURE (IN.)	Tight to 1 in.
I. EVIDENCE OF JOINT SEEPAGE	no
J. PRESENCE & TYPE JOINT INFILLING SOILS	no
K. EVIDENCE OF ROOT JACKING	At top of slope due to close-spaced partings on J_1
L. VEGETATION IN/ON JOINTS	Yes. See 2G above
M. ROCK SURFACE ROUGHNESS - MICROSCALE	SM-PO on J_1 faces; ST if @ angle To J_1 (PL)
N. ROCK SURFACE ROUGHNESS - MACRO (JRC)	Most faces "rough" & ST/W (>JCR)
O. GEOLOGIC STRUCTURE	Foliated & jointed sheets gen. < 12" max thick

4. SOIL OBSERVATIONS

A. SOIL TYPE & CLASS.	Hi.wx rock & organics
B. OVERBURDEN THICKNESS (FT.)	<18 in @ brow of slope but spotty dist.

5. EVIDENCE OF ICE DEVELOPMENT

A. STRIPPED VEGETATION OR SOIL	Two small trees (2"0) fell-out.poss just erosion & sloughing
B. CONTORTED TREE GROWTH	None obs.
C. POLISHED/GROOVED ROCK SURFACES	None obs.
D. OBS. ICE JACKING OF ROCK BLOCKS	Ice app.to be weaging open J_1 at top of slope
E. SITE HISTORY OF ICE DEVELOP/ICEFALL	Yes; ice develop.slabs have heaved soil as they fail and push into soil "Belugas"

6. ROCKFALL CATCHMENT

A. EFFECTIVE DITCH WIDTH (FT.)	20'-21'
B. EFFECTIVE DITCH HEIGHT (FT.)	3'
C. EXISTING DITCH CONDITION	PARTLY FILLED <1% v.minor sloughing of slatey/Wx rock
D. OBS. DAMAGE TO ROADWAY	No
E. SITE HISTORY OF ROCKFALL	Only minor raveling of loose rock. All maint. by ditch

7. GENERAL COMMENTS ON SITE

1. Portions of cut w/sheared/smooth-pol.fabric are mildly graphitic.
2. Although indiv.portions of slope face furried by J_1 are smooth, large-scale roughness is high b/c slabs/sheets of rock are weak ⍰ to J_1, and break there as result. Ends up being stepped & wavy over slope height
3. Culvert @ north end est.term point; crest of hill est.term.point on south end (approx.).

Note: Ditch width in initil field notes included 3 ft of unpaved shoulder. Add this to ditch width.

CLIENT NAME AND DIVISION:	Alaska DOT&PF/RESEARCH	**STAFF:**	D. SCARPATO
PROJECT NAME:	PHASE 2 - SITE SPECIFIC ICEFALL HAZARD EVALUATION	**DATE:**	9/17/2016
HIGHWAY:	Seward	**WEATHER:**	p. cloudy, showers >40s calm winds
MILEPOST/MILEPOINT NO.:	~57.9-58.2 ±		
SIDE OF HIGHWAY:	Northbound		
AS-BUILT RECORDS EXIST:	YES		

1. ROADWAY OBSERVATIONS:

A. EFFECTIVE ROADWAY WIDTH (FT.)	38 ft paved; 12 ft lanes
B. NUMBER OF LANES	2
C. EFFECTIVE SHOULDER WIDTH (FT.)	7 ft northbound side (both sides N&S)
D. PRESENCE OF HORIZ./VERT. CURVES	Yes; HC; almost no VC; northbound max sight dist.~700 ft
E. POSTED SPEED LIMIT (MPH)	65 but drive much faster @ 75-85mph

2. SLOPE OBSERVATIONS

A. EFFECTIVE ROADWAY LENGTH (FT.)	Approx. 500 ft.
B. SLOPE HEIGHT RANGE [MIN/MAX/AV] (FT.)	15 ft (min@ends); 120 ft max (middle)
C. SLOPE PROFILE IN PLAN & SECTION	Curved concave inward (plan); linear w/bench (section)
D. PRESENCE OF BACKSLOPE	Yes, on ends; middle is rel.flat
E. SLOPE MATERIAL:	ROCK
F. SLOPE ANGLE RANGE (MIN/MAX/AV)	70° BFA & main slope; 65° overall where benched
G. PRESENCE & TYPES OF VEGETATION	At brows and ends of slope. Saplings/grass, local moss no big trees
H. SLOPE ASPECT & DIP DIRECTION	NE - see notes
I. PRESENCE OF INT. SEEPAGE & SOURCE	Yes; not flowing just very wet localized
J. PRESENCE OF SURFACE WATER & SOURCE	On both ends of cut water is flowing
K. EVIDENCE OF SLOPE INSTABILITY & TYPE(S)	Just minor raveling. Structure orientation is idea WRT roadway

3. BEDROCK OBSERVATIONS

A. ROCK LITHOLOGY/TYPE/UNIT	Late K sed.rock (Valdez group); app.slate; book says turbidite dep.
B. ROCK COLOR	Dark gray to light gray
C. FIELD EST. COMP. STRENGTH (PSI)	R2 to R4 (where coarser grained & thicker)
D. WEATHERING/ALT. INDEX	W2-W3 (50:50)
E. CRYSTALLINE TEXTURE OR FABRIC	Laminated/fissile/sheared fabric @ northend; graywacke @ south
F. NO. OF DISCONTINUITY SETS	3 primary +>FXS
G. DISCONTINUITY SET ORIENTATIONS	J_1 (bedding) @ 092/72; J_2 @ 343/85; J_3 @ 354/27
H. EST. JOINT APERTURE (IN.)	Hi. variable; tight to open 4"
I. EVIDENCE OF JOINT SEEPAGE	Yes; localized, esp. middle of slope length
J. PRESENCE & TYPE JOINT INFILLING SOILS	No
K. EVIDENCE OF ROOT JACKING	No
L. VEGETATION IN/ON JOINTS	Minor - see 2G above
M. ROCK SURFACE ROUGHNESS - MICROSCALE	SM @ northend; Rough @ southend
N. ROCK SURFACE ROUGHNESS - MACRO (JRC)	>JCR
O. GEOLOGIC STRUCTURE	Bedded; mildly contorted undulating bedding

4. SOIL OBSERVATIONS

A. SOIL TYPE & CLASS.	NA
B. OVERBURDEN THICKNESS (FT.)	Minimal if any. Looks like all rock

5. EVIDENCE OF ICE DEVELOPMENT

A. STRIPPED VEGETATION OR SOIL	No
B. CONTORTED TREE GROWTH	No
C. POLISHED/GROOVED ROCK SURFACES	No
D. OBS. ICE JACKING OF ROCK BLOCKS	Bedding/fols opened by frost action @ browns
E. SITE HISTORY OF ICE DEVELOP/ICEFALL	Yes; ice dev.around midslope bench.

6. ROCKFALL CATCHMENT

A. EFFECTIVE DITCH WIDTH (FT.)	19 ft (ends) to 26 ft (middle)
B. EFFECTIVE DITCH HEIGHT (FT.)	3 ft to 3.5 ft
C. EXISTING DITCH CONDITION	PARTLY FILLED 2-3% minimal debris
D. OBS. DAMAGE TO ROADWAY	No
E. SITE HISTORY OF ROCKFALL	Not freq., rel small events from raveling

7. GENERAL COMMENTS ON SITE

1. Slope constructed in mid-1990s
2. Ice build-up at this site per Keven Notek; gets hung-up on mid-slope const.bench. Fragments have made it to the fog line. Sheets form at this site. Occ.snow slides- covered car a few years back.
3. North end of segment has stream flowign down toward roadway, but culvert is present (under road).
4. Slope dip direction: (insert picture?)
5. "Fault" orientation (approx.) @ ST.225/80 (DD~135°).
Flowing water @ trickle
Open 6" - 3 ft at top; filled w/plast.matrix (silt) & crushed rock.
6. Bench - approx. 1/2 slope length; sloping toward road @~30°; widest @ north end @~15 ft; rest slope has bench <3'-4' wide.
7. 4th discon. @ far north end; 021/79 (not seen rest of cut)

Notes: 1. cut is oblique to strike of bedding planes. Results in rough slope profile.
2. Ditch width in initil field notes included 3 ft of unpaved shoulder. Add this to ditch width.

CLIENT NAME AND DIVISION:	Alaska DOT&PF/RESEARCH		**STAFF:**	D. SCARPATO
PROJECT NAME:	PHASE 2 - SITE SPECIFIC ICEFALL HAZARD EVALUATION		**DATE:**	9/18/2016
HIGHWAY:	Seward	starts @ north end @ MP75- 640 ft	**WEATHER:**	P. Cloudy
MILEPOST/MILEPOINT NO.:	74.1 - 74.9 total	ends @ south end @ MP 74 - 385 ft		<50s
SIDE OF HIGHWAY:	Southbound			calm winds
AS-BUILT RECORDS EXIST:	YES			

1. ROADWAY OBSERVATIONS:

A. EFFECTIVE ROADWAY WIDTH (FT.)	11 ft. lane widths; 44 ft. paved width
B. NUMBER OF LANES	3; 2 uphill southbound; 1 downhill northbound
C. EFFECTIVE SHOULDER WIDTH (FT.)	7 ft. west side (paved @ 3'+4' agg.base); 8 ft. paved east side
D. PRESENCE OF HORIZ./VERT. CURVES	Both; HC radii are small; VC = downhill leg
E. POSTED SPEED LIMIT (MPH)	65 but people drive much faster

2. SLOPE OBSERVATIONS

A. EFFECTIVE ROADWAY LENGTH (FT.)	0.8 mi±; but primary slope w/H20 @ MP 74.8
B. SLOPE HEIGHT RANGE [MIN/MAX/AV] (FT.)	15 ft - 75 ft. See field notes
C. SLOPE PROFILE IN PLAN & SECTION	Plan is gen.linear; profile hi.variable except planar/lin.@ main waterfall
D. PRESENCE OF BACKSLOPE	Yes; angle hi.variable
E. SLOPE MATERIAL: main cut face =	ROCK
F. SLOPE ANGLE RANGE (MIN/MAX/AV)	55° - near vertical. See field notes
G. PRESENCE & TYPES OF VEGETATION	Many small saplings. Moss in moist areas
H. SLOPE ASPECT & DIP DIRECTION	Road trend @ 215° AZ overall; 125 (SE) dip direction
I. PRESENCE OF INT. SEEPAGE & SOURCE	Locally - see field notes
J. PRESENCE OF SURFACE WATER & SOURCE	Yes; locally, see field notes
K. EVIDENCE OF SLOPE INSTABILITY & TYPE(S)	Just small-scale rockfall from slope raveling

3. BEDROCK OBSERVATIONS *at primary wet areas/south of hi-tension lines

A. ROCK LITHOLOGY/TYPE/UNIT	Late K Valdez group, sed.rocks. Slately @ south end; closer to graywacke @ MP74.8
B. ROCK COLOR	Light to dark gray
C. FIELD EST. COMP. STRENGTH (PSI)	R4-R5
D. WEATHERING/ALT. INDEX	W1-W2
E. CRYSTALLINE TEXTURE OR FABRIC	Aphanitic; laminated/slately cleavage just N/S of waterfall
F. NO. OF DISCONTINUITY SETS	5 primary + random fx's
G. DISCONTINUITY SET ORIENTATIONS	See notes below
H. EST. JOINT APERTURE (IN.)	Typ.is tight to 3" wide
I. EVIDENCE OF JOINT SEEPAGE	Only locally. Not freq. see field notes
J. PRESENCE & TYPE JOINT INFILLING SOILS	No
K. EVIDENCE OF ROOT JACKING	No
L. VEGETATION IN/ON JOINTS	Yes; saplings & moss along persistent joints
M. ROCK SURFACE ROUGHNESS - MICROSCALE	R-VR; PL-ST-UN. Sandy texture
N. ROCK SURFACE ROUGHNESS - MACRO (JRC)	Mod.to hi. JCR; except waterfall; smooth
O. GEOLOGIC STRUCTURE	Massive, jointed bedrock. Cannot discern bedding at prim. waterfall feature area but can 200' south.

4. SOIL OBSERVATIONS

A. SOIL TYPE & CLASS.	Sandy soil & broken rock frags at ends of slope; medial shows little soil dev.
B. OVERBURDEN THICKNESS (FT.)	< 2ft

5. EVIDENCE OF ICE DEVELOPMENT

A. STRIPPED VEGETATION OR SOIL	Prim. from water flow
B. CONTORTED TREE GROWTH	No
C. POLISHED/GROOVED ROCK SURFACES	No
D. OBS. ICE JACKING OF ROCK BLOCKS	No
E. SITE HISTORY OF ICE DEVELOP/ICEFALL	Yes; primarily @ waterfall feature @ MP 74.8 No icefall in roadway based on AKDOT

6. ROCKFALL CATCHMENT - *total site

A. EFFECTIVE DITCH WIDTH (FT.)	17 ft - 27 ft
B. EFFECTIVE DITCH HEIGHT (FT.)	2.0 ft - 4.0 ft
C. EXISTING DITCH CONDITION	PARTLY FILLED <2% very minor amt debris
D. OBS. DAMAGE TO ROADWAY	No
E. SITE HISTORY OF ROCKFALL	Infrequent - Small raveling events along bedding

7. GENERAL COMMENTS ON SITE

1. CMP culvert defines northern extent.
2. Second culvert west side road w/running stream but between cut faces at local low spot.
3. Culvert on south end/top of hill @~ MP 74.05 ± defines southern limit of sig.rock cut.
4. Note that only location with/sig. water flow discharging on slope face is ~MP 74.
5. Site distances are not obstructed.
6. Primary ice build-up zone @ MP 74.8
   - slope height = 35 ft
   - ditch width = 20 ft
   - ditch depth = 4.0 ft
7. Debris "saddle" @~1300' N or MP 74. Rock debris & veg.; water seepage; adj.culvert @ base. Seepage @ lower/0' of slope.

J_1 = 060/31
J_2 = 198/85
J_6 = 129/64°-80°
J_3 = 053/72
J_4 = 120/88* (forms top 2/3 of waterfall face)
J_5 = 022/45 bedding

Note: Ditch width in initil field notes included 2 ft of unpaved shoulder. Add this to ditch width as shown in as-builts.

APPENDIX NO. 2

Site Visit No. 2

Ice Slab Field Data

Alaska DOT&PF
Phase No. 2 - Prelim. Icefall Hazard Evaluations
Appendix 2 - Ice Slab Field Data
Sheet 1 of 2

2/24/2018

									ICE SUPPORT CONDITION					
SITE	**DATE**	**WEATHER**	**APPROX. TEMP. (°F)**	**SUBSEGMENTS**	**SLOPE ASPECT(2)**	**ICE LOCATION**	**PRIMARY WATER SOURCE**	**FORMATION**	**STRUCTURE COMPONENT**	**INTERFACE COMPONENT**	**COLOR**	**QUALITATIVE ICE STRENGTH**	**SITE HISTORY OF ICEFALL IN ROADWAY**	**ACTIVE SLOUGHING WHILE ONSITE**
MP 113.1 – MP113.3 SEW	3/13/2017	Sun	25	1	South-Southwest (207° AZ.)	Upper & Medial	Joint intercept & direct overflow of upslope water	Amorphous	Base (Benching) & Top	Partial Adhesion	White to Gray	Low	Yes - Large Slabs	Yes - <24 in. dia.
MP 74.1 – MP 74.9 SEW	3/17/2017	Sun	20	1	South-Southeast (142° AZ.)	Full Height	Joint intercept & direct overflow of upslope water	Slab	Full Height	Full Adhesion	White	High	No	No
				2		Upper & Medial		Overhang	Top	Partial Adhesion	Brown, Dirty	Medium		
				3		Full Height		Slab	Base & Top	Partial Adhesion	White to Clear	High		
MP 57.9 – MP 58.2 SEW	3/18/2017	P. Cloudy, Lt. Wind	10	1	Northeast (37° - 62° AZ.)	Full Height	Direct Overflow of Upslope Water	Slab	Full Height	Full Adhesion	Blue to White	High	No	No
				2					Base					
				3		Lower	Joint intercept		None		White to Gray	Medium		
				4		Full Height	Direct Overflow of Upslope Water		Base & Top		White	High		
MP 51.9 – MP 52.3 SEW	3/20/2017	Sun	21	1	East-Southeast (97° AZ.)	Full Height	Direct Overflow of Upslope Water	Slab	Base & Top	Partial Adhesion	Blue to White	Medium	Yes - Ice Slabs	No
				2							White	Low to Medium		
MP 38.3 – MP 38.5 RICH	3/14/2017	Sun, Wind	5	1	South-Southwest (192° AZ.)	Full Height	Direct Overflow of Upslope Water	Slab	Base	Full Adhesion	Blue	High	Yes - Small Fragments	No
				2					Full Height					
				3		Upper & Medial		Overhang	Top	Partial Adhesion	White & Brown	Medium		
				4						Full Adhesion	Blue	High		
MP 22.7 – MP 23.3 RICH	3/16/2017	Sun, Wind	8	1	South-Southeast (166° AZ.)	Medial & Lower	Direct Overflow of Upslope Water	Slab	Base (Benching)	Partial Adhesion	Blue to White	Medium	Yes - Small Fragments	No
				2		Medial		Amorphous	Base (Benching)	Partial Adhesion	White	Low to Medium		
				3		Full Height		Overhang	Top	Partial Adhesion	Blue to White	Medium		
				4		Lower		Slab	Base	Full Adhesion	Blue	High		
				5		Medial & Lower		Slab	None	Partial Adhesion	Blue to White	Low		
MP 13.7 – MP 14.0 RICH	3/15/2017	Clouds, Wind	10	1	East-Northeast (80° - 92° AZ.)	Interspersed, Localized	Joint intercept & direct overflow of upslope melt water	Amorphous & Icicles	Top	Partial Adhesion	White to Gray to Clear	Low	Yes - Ice Blocks	Yes - Small Fragments

Notes:

1. Measurments where shown are approx. and average.
2. Aspect azimuth corrected to true north by accounting for magnetic declination (+17 deg.)

Alaska DOT&PF
Phase No. 2 - Prelim. Icefall Hazard Evaluations
Appendix 2 - Ice Slab Field Data
Sheet 2 of 2

2/24/2018

	APPROX. SLAB GEOMETRY BASED ON MARCH 2017 OBS.[1]													
	APPROX. ICE COVERAGE	HEIGHT (FT.)			WIDTH (FT.)			THICKNESS (FT.)			CONTACT AREA (S.F.)	VOLUME (C.F.)	VOLUME (C.Y.)	WEIGHT (KIPS)
SITE		MIN.	MAX.	AVERAGE	MIN.	MAX.	AVERAGE	MIN.	MAX.	AVERAGE				
MP 113.1 – MP113.3 SEW	1.2%	42	43	42.5	20	32	26	1.0	6.0	3.5	1,105	3,868	143	221
MP 74.1 – MP 74.9 SEW	0.3%	27	27	27	22	22	22	1.0	9.0	5.0	594	2,970	110	170
	0.3%	27	27	27	18	18	18	1.0	2.5	1.8	486	851	32	49
	0.3%	27	27	27	24	24	24	1.0	5.0	3.0	648	1,944	72	111
	0.9%										1,728	5,765	214	330
MP 57.9 – MP 58.2 SEW	3.3%	28	28	28	63	63	63	5.0	12.0	8.5	1,764	14,994	555	858
	2.0%	27	27	27	39	39	39	3.0	5.0	4.0	1,053	4,212	156	241
	0.1%	30	30	30	1	4	2.5	2.0	4.0	3.0	75	225	8	13
	0.9%	12	12	12	39	39	39	1.0	4.0	2.5	468	1,170	43	67
	6.2%										3,360	20,601	763	1,178
MP 51.9 – MP 52.3 SEW	8.8%	16	20	18	100	100	100	1.0	4.0	2.5	1,800	4,500	167	257
	4.5%	8	22	15	62	62	62	1.0	4.0	2.5	930	2,325	86	133
	13.3%										2,730	6,825	253	390
MP 38.3 – MP 38.5 RICH	2.6%	29	29	29	33	33	33	1.0	7.0	4.0	957	3,828	142	219
	1.2%	6	20	13	35	35	35	2.0	6.0	4.0	455	1,820	67	104
	3.6%	27	27	27	50	50	50	0.5	4.0	2.3	1,350	3,038	113	174
	0.9%	22	22	22	16	16	16	4.0	4.0	4.0	352	1,408	52	81
	8.4%										3,114	10,094	374	577
MP 22.7 – MP 23.3 RICH	0.9%	33	33	33	30	30	30	1.0	3.0	2.0	990	1,980	73	113
	0.6%	23	23	23	30	30	30	0.5	2.5	1.5	690	1,035	38	59
	0.8%	20	20	20	46	46	46	1.0	3.5	2.3	920	2,070	77	118
	0.3%	16	16	16	23	23	23	1.0	9.0	5.0	368	1,840	68	105
	1.8%	20	20	20	100	100	100	1.0	1.0	1.0	2,000	2,000	74	114
	4.5%										4,968	8,925	331	511
MP 13.7 – MP 14.0 RICH	<1%	1	5	3	1	3	2	1.0	3.0	2.0	6	12	0.4	0.7

Notes:

1. Dimensions shown are approx. and average.

APPENDIX NO. 3

Degree Day Calculations

Alaska DOT&PF
Phase No. 2 - Prelim. Icefall Hazard Evaluations
Appendix 3 - Degree Day Calculations
Sheet 1 of 1

2/27/2018

Weather Data McHugh Creek RWIS @ MP 111.8							
Ref. Temp. (Deg. F)	**2012**	**Air Temp. (deg. F)**			**Melting DD (deg. F)**		
32	Day	high	Low	Average	DD_{raw}	DD_{corr}	Cum. DD
March	18	30	20	25	-7	0	0
	19	26	21	23.5	-8.5	0	0
	20	25	20	22.5	-9.5	0	0
	21	29	14	21.5	-10.5	0	0
	22	27	17	22	-10	0	0
	23	32	20	26	-6	0	0
	24	42	27	34.5	2.5	2.5	2.5
	25	35	22	28.5	-3.5	0	2.5
	26	38	23	30.5	-1.5	0	2.5
	27	37	29	33	1	1	3.5
	28	45	35	40	8	8	11.5
	29	47	37	42	10	10	21.5
	30	42	30	36	4	4	25.5
	31	41	36	38.5	6.5	6.5	32
April	1	42	33	37.5	5.5	5.5	37.5
	2	39	30	34.5	2.5	2.5	40
	3	40	29	34.5	2.5	2.5	42.5
	4	41	30	35.5	3.5	3.5	46
	5	41	37	39	7	7	53
	6	42	34	38	6	6	59
	7	36	31	33.5	1.5	1.5	60.5
	8	41	30	35.5	3.5	3.5	64
	9	43	29	36	4	4	68
	10	40	25	32.5	0.5	0.5	68.5
	11	42	30	36	4	4	72.5
	12	43	32	37.5	5.5	5.5	78

Weather Data Keystone Canyon RWIS @ MP 12.3							
Ref. Temp. (Deg. F)	**2017**	**Air Temp. (deg. F)**			**Melting DD (deg. F)**		
32	Day	high	Low	Average	DD_{raw}	DD_{corr}	Cum. DD
November	26	15	10	12.5	-19.5	0	0
	27	30	13	21.5	-10.5	0	0
	28	35	27	31	-1	0	0
	29	35	31	33	1	1	1
	30	34	28	31	-1	0	1
December	1	30	23	26.5	-5.5	0	1
	2	32	23	27.5	-4.5	0	1
	3	41	28	34.5	2.5	2.5	3.5
	4	41	35	38	6	6	9.5
	5	38	32	35	3	3	12.5
	6	40	32	36	4	4	16.5
	7	40	33	36.5	4.5	4.5	21
	8	40	33	36.5	4.5	4.5	25.5
	9	43	33	38	6	6	31.5
	10	42	35	38.5	6.5	6.5	38
	11	42	32	37	5	5	43
	12	39	31	35	3	3	46
	13	43	33	38	6	6	52

APPENDIX NO. 4

Preliminary Icefall Impact Risk Matrix

Alaska DOT&PF
Phase No. 2 - Prelim. Icefall Hazard Evaluations
Appendix 4 - Preliminary Icefall Impact Risk Matrix (PIIRM)
Sheet 1 of 1

SCARP TEC
ROCK ENGINEERING SOLUTIONS

2/22/2018

Site	Annual Ice Recurrance	History of Icefall Impacts to Roadway	Type	AADT[1]	Est. No. Vehicles/ Hour	Min. Est. Sight[2] Distance (ft.)	Slope Height, H (ft.)			Catchment Ditch Width, w (ft.)			(H/w)[3] Ratio	R (ft.)	(H/R)[4] Ratio	Prelim. Risk Ranking
							Min.	**Max.**	**Av.**	**Min.**	**Max.**	**Av.**	**Ideal < 4.0**		**Ideal < 2.5**	
MP 113.1 – MP113.3 SEW	Yes	YES	Direct	9283	544	1250	50	140	95	8	14	11	8.6	29	3.3	HIGH
MP 74.1 – MP 74.9 SEW	Yes	NO	None	3930	230	1150	15	75	45	17	27	22	2.0	47	1.0	LOW
MP 57.9 – MP 58.2 SEW	Yes	NO	None	3600	211	850	15	120	68	19	26	23	3.0	42	1.6	LOW
MP 51.9 – MP 52.1 SEW	Yes	YES	Direct	3600	211	4000	11	30	21	23	24	24	0.9	52	0.4	LOW-MOD
MP 38.3 – MP 38.5 RICH	Yes	NO	None	445	26	2000	20	73	47	31	31	31	1.5	49	0.9	LOW
MP 22.7 – MP 23.3 RICH	Yes	YES	Shatter	445	26	2600	35	50	43	35	40	38	1.1	54	0.8	LOW
MP 13.7 – MP 14.0 RICH	Yes	YES	Direct	640	37	600	102	189	146	14	22	18	8.1	34	4.3	MOD-HIGH

Notes:

[1] Based on AADT data for 2013 (from CR Annual Traffic Vol. Report 2011-2013).

[2] Sight distance in middle of interval for lane on the slope side of highway, measured in the field.

[3] Measured slope height (H) to effective ditch width (w) ratio based on averages.

[4] Slope height (H) to roadway centerline offset (R) ratio. "R" is measured from road CL to int. with slope face.

APPENDIX NO. 5

Section Geometry

Alaska DOT&PF
Phase No. 2 - Prelim. Icefall Hazard Evaluations
Appendix 5 - Section Geometry
Sheet 1 of 1

2/22/2018

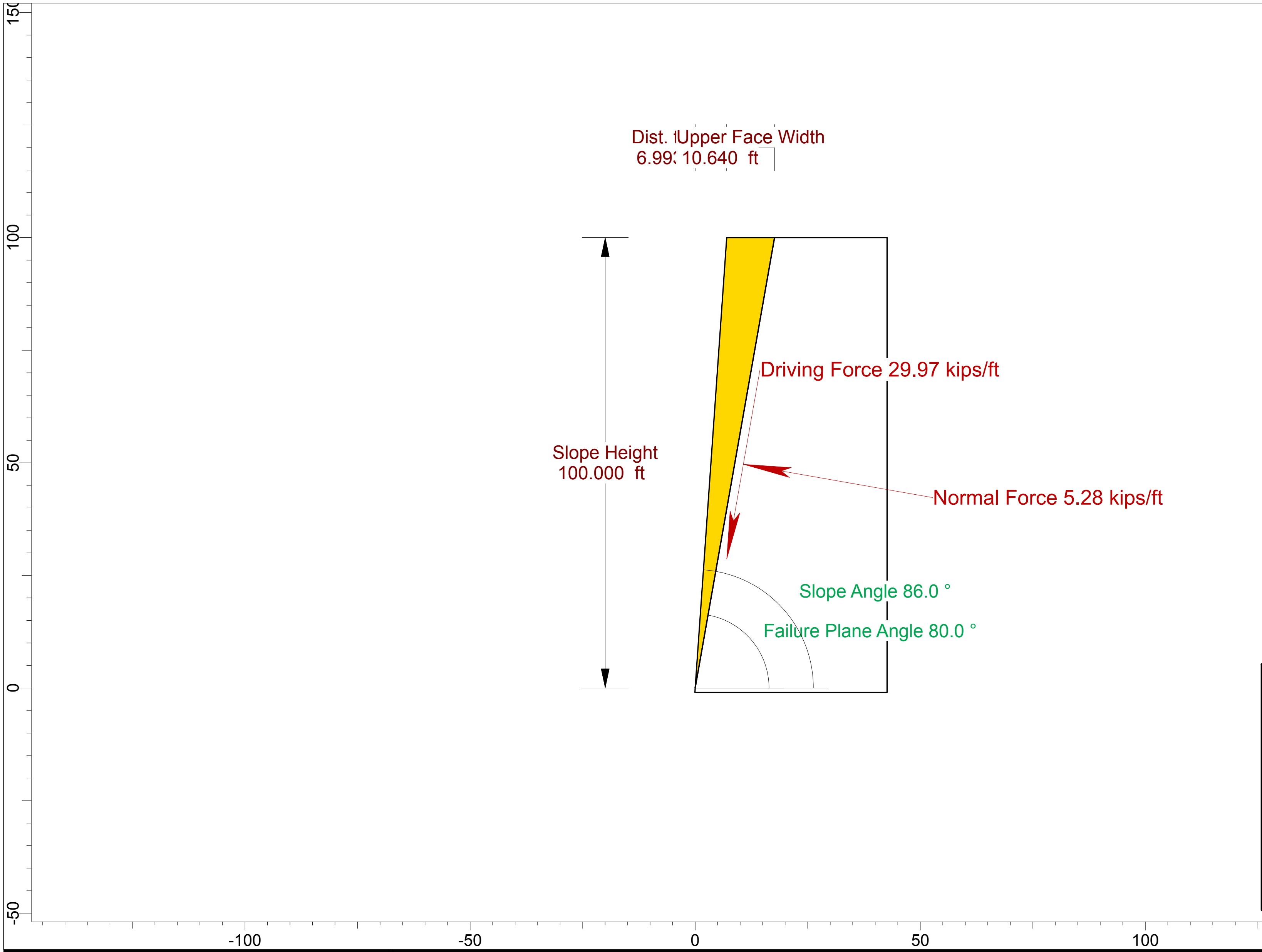
SITE	MP OF CRITICAL SECTION	SLOPE GEOMETRY(1)							ROADWAY GEOMETRY (3)			CATCHMENT DITCH GEOMETRY(5)					
		HEIGHT (FT.)				OVERALL SLOPE			ROAD WIDTH(2) (FT.)	SLOPE TOE TO CENTERLINE DISTANCE (4) (FT.)	EFFECTED ROAD LENGTH (FT.)	WIDTH(6) (FT.)			DEPTH (FT.)		
		MIN.	MAX.	AVERAGE	CRITICAL SECTION	MIN.	MAX.	CRITICAL SECTION				MIN.	MAX.	CRITICAL SECTION	MIN.	MAX.	CRITICAL SECTION
MP 113.1 – MP113.3 NB SEW	113.2	50	140	95	100	70	88	86	54 (90)	29	1000	8	14	10	0	3	3
MP 74.1 – MP 74.9 SB SEW	74.8	15	75	45	35	55	90	85	44	47	4200	17	27	24	2	4	4
MP 57.9 – MP 58.2 NB SEW	57.9	15	120	68	33	65	73	73	38	42	800	19	26	20	3	3.5	3
MP 51.9 – MP 52.3 SB SEW	52.0	11	30	21	22	75	80	80	48	52	1000	23	24	23	3	3	3
MP 38.3 – MP 38.5 SB RICH	38.4	20	73	47	34	65	72	70	36	49	800	31	31	31	4	4.5	4
MP 22.7 – MP 23.3 SB RICH	23.0	35	50	43	47	70	85	80	36	54	2600	35	40	35	5	6	5
MP 13.7 – MP 14.0 SB RICH	13.9	102	189	146	112	50	90	70	32	34	1300	14	22	18	3	5.5	5

Notes:

1. Slope geometry derived from Scarptec's field measurements and AKDOT&PF as-built plans.
2. Includes paved shoulder to paved shoulder. If available, turnout width shown in "(#)".
3. Based on average of measurements within interval and available as-built plans.
4. Distance based on assumed centerline at lane divider/double yellow line.
5. Ditch section geometry may be reduced in winter months due to ice and snow from removal and plowing operations.
6. Ditch width includes portion of unpaved shoulder if present.
7. Distances shown above are approximate.

APPENDIX NO. 6

Ice Sliding Analyses



Factor of Safety	1.02
Driving Force	29.97 kips/ft
Resisting Force	30.46 kips/ft
Wedge Weight	30.43 kips/ft
Wedge Volume	532.00 ft^3/ ft
Shear Strength	0.30 ksf
Shear Resistance	30.46 kips/ft
Normal Force	5.28 kips/ft
Plane Waviness	0.0°

rocscience

ROCPLANE 3.006

Project	AKDOT&PF - MP 113.2		
Analysis Description	Icefall Sliding		
Drawn By	D. Scarpato, P.E.	*Company*	Scarptec, Inc.
Date	1/12/2018, 4:55:24 PM	*File Name*	RocPlane1

RocPlane Analysis Information

AKDOT&PF - MP 113.2

Project Summary

File Name	RocPlane1
Project Title	AKDOT&PF - MP 113.2
Analysis	Icefall Sliding
Author	D. Scarpato, P.E.
Company	Scarptec, Inc.
Date Created	1/12/2018, 4:55:24 PM

Analysis Results

Analysis Type - Deterministic

Normal Force	5.28419 kips/ft
Driving Force	29.9681 kips/ft
Resisting Force	30.4628 kips/ft
Factor of Safety	1.01651

Geometry

Slope Height	100 ft
Wedge Weight	30.4304 kips/ft
Wedge Volume	532.001 ft^3/ft
Wedge Height	100 ft
Unit Weight	0.0572 kips/ft3
Slope Angle	86 °
Failure Plane Angle	80 °
Upper Face Angle	0 °
Bench Width	Not Present
Waviness	0 °
Intersection Point (B) of slope and upper face	(6.99268 , 100)
Intersection point (C) of failure plane and upper face	(17.6327 , 100)
Failure plane length (Origin --> C)	101.543 ft
Slope length (Origin --> B)	100.23 ft
Tension Crack	Not Present

Strength

Shear Strength Model	Mohr-Coulomb
Friction Angle	0 °
Cohesion	0.3 kips/ft2
Shear Strength	0.3 kips/ft2
Shear Resistance	30.4628 kips/ft

Factor of Safety	36.59
Driving Force	29.97 kips/ft
Resisting Force	1096.66 kips/ft
Wedge Weight	30.43 kips/ft
Wedge Volume	532.00 ft^3/ ft
Shear Strength	10.80 ksf
Shear Resistance	1096.66 kips/ft
Normal Force	5.28 kips/ft
Plane Waviness	0.0°

rocscience

ROCPLANE 3.006

Project	AKDOT&PF - MP 113.2		
Analysis Description	Icefall Sliding		
Drawn By	D. Scarpato, P.E.	*Company*	Scarptec, Inc.
Date	1/12/2018, 4:55:24 PM	*File Name*	RocPlane1

RocPlane Analysis Information

AKDOT&PF - MP 113.2

Project Summary

File Name	RocPlane1
Project Title	AKDOT&PF - MP 113.2
Analysis	Icefall Sliding
Author	D. Scarpato, P.E.
Company	Scarptec, Inc.
Date Created	1/12/2018, 4:55:24 PM

Analysis Results

Analysis Type - Deterministic

Normal Force	5.28419 kips/ft
Driving Force	29.9681 kips/ft
Resisting Force	1096.66 kips/ft
Factor of Safety	36.5942

Geometry

Slope Height	100 ft
Wedge Weight	30.4304 kips/ft
Wedge Volume	532.001 ft^3/ft
Wedge Height	100 ft
Unit Weight	0.0572 kips/ft3
Slope Angle	86 °
Failure Plane Angle	80 °
Upper Face Angle	0 °
Bench Width	Not Present
Waviness	0 °
Intersection Point (B) of slope and upper face	(6.99268 , 100)
Intersection point (C) of failure plane and upper face	(17.6327 , 100)
Failure plane length (Origin --> C)	101.543 ft
Slope length (Origin --> B)	100.23 ft
Tension Crack	Not Present

Strength

Shear Strength Model	Mohr-Coulomb
Friction Angle	0 °
Cohesion	10.8 kips/ft2
Shear Strength	10.8 kips/ft2
Shear Resistance	1096.66 kips/ft

APPENDIX NO. 7

Impact Force & Energy Calculations

Alaska DOT&PF
Phase No. 2 - Prelim. Icefall Hazard Evaluations
Appendix 7 - Icefall Impact Force & Energy Calculator
Sheet 1 of 1

2/22/2018

SECTION NO. MP 113.2

A.1 Free-Fall Calculation:

BLOCK PROPERTIES								**INSTANT. VELOCITY**				**FALL TIME**	**IMPACT ENERGY**
$V_{cube} = HWT$ OR $V_{sphere} = 4/3 \pi r^3$					$M = \rho V$		$W = MG$	$v_i = \sqrt{(2GD)}$				$T_i = \sqrt{(2D/G)}$	$KE = 0.5MV^2$
DIMENSIONS			VOLUME		DENSITY	MASS	WEIGHT	GRAV. ACC.	FALL DIST.		VELOCITY	TIME TO IMPACT	KINETIC ENERGY
H (FT)	W (FT)	T (FT)	V (CF)	V (CM)	ρ (KG/M^3)	M (KG)	W (KIPS)	G (M/S^2)	D (FT)	D (M)	V_i (M/S)	T_i (S)	KE (KJ)
5.7	17.1	4.0	390	11	916	10,117	22.3	9.81	45	14	16.4	1.7	1,361

A.2 Impact Force Estimate:

			Fi = KE/S	
KINETIC ENERGY		**STOP DIST.**	**IMPACT FORCE**	
KE (KJ)	**KE (FT-LBS)**	**S or δ (FT)**	**Fi (LBS)**	**Fi (KIPS)**
1,361	1,003,990	1	1003990	1004
		2	501995	502
		3	334663	335
		4	250998	251
		5	200798	201
		6	167332	167
		7	143427	143

SECTION NO. MP 13.9

A.1 Free-Fall Calculation:

BLOCK PROPERTIES								INSTANT. VELOCITY				FALL TIME	IMPACT ENERGY
$V_{cube} = HWT$ OR $V_{sphere} = 4/3 \pi r^3$					$M = \rho V$		$W = MG$	$v_i = \sqrt{(2GD)}$				$T_i = \sqrt{(2D/G)}$	$KE = 0.5MV^2$
DIMENSIONS			VOLUME		DENSITY	MASS	WEIGHT	GRAV. ACC.	FALL DIST.		VELOCITY	TIME TO IMPACT	KINETIC ENERGY
H (FT)	W (FT)	T (FT)	V (CF)	V (CM)	ρ (KG/M^3)	M (KG)	W (KIPS)	G (M/S^2)	D (FT)	D (M)	V_i (M/S)	T_i (S)	KE (KJ)
20.0	8.0	3.0	480	14	916	12,455	27.5	9.81	20	6	10.9	1.1	745

A.2 Impact Force Estimate:

			Fi = KE/S	
KINETIC ENERGY		**STOP DIST.**	**IMPACT FORCE**	
KE (KJ)	**KE (FT-LBS)**	**S or δ (FT)**	**Fi (LBS)**	**Fi (KIPS)**
745	549,360	1	549360	549
		2	274680	275
		3	183120	183
		4	137340	137
		5	109872	110
		6	91560	92
		7	78480	78